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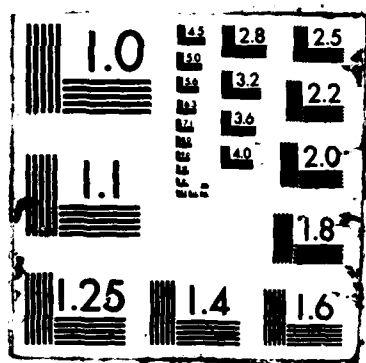
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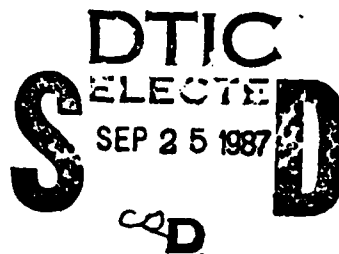
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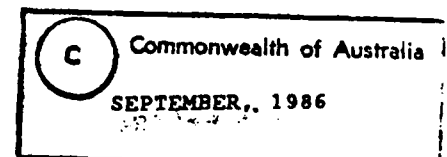
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**A COMPUTER-INTERACTIVE, SINGLE SPECIMEN J-INTEGRAL
FRACTURE TOUGHNESS TEST**

D.S. Saunders and I.A. Burch



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ABSTRACT

This report outlines the development of a computer-interactive, single specimen J-integral fracture toughness test method. The test method was developed on a PDP 11/04 computer and MTS 810 servo-hydraulic test machine using compact tension specimens machined from a NiMoCr gun steel. The report discusses some of the theoretical concepts of the J-integral, particularly those which are relevant to the test method which involves the measurement of area under the load/load-line-displacement curve and the measurement of crack extension. The report also discusses in detail some of the errors within the computer-interactive, single specimen J-integral test method and how these can be reduced. It is concluded that the test method permits the evaluation of the J-integral fracture toughness of high strength steels in accordance with the existing (ASTM) standard.

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LIST OF SYMBOLS

a	-	crack length
a ₀	-	initial crack length
a _f	-	final crack length
Δa	-	a _f - a ₀ = crack extension
A	-	area under load/load-line-displacement record
b	-	uncracked ligament length
B	-	specimen thickness
CTOD	-	crack tip opening displacement
E	-	Young's modulus
E'	-	E/(1 - ν ²)
Err%	-	error in measurements
$\tilde{E}(\theta, n)$	-	non-dimensional function of θ and n
I _n	-	coefficient of strain hardening stress intensity
J	-	J-integral value
J _c	-	critical value of J
J _{IC}	-	critical value of J measured in Mode I opening
K	-	stress intensity factor
K _{IC}	-	critical value of K measured in Mode I opening and by definition is used as a measure of plane strain fracture toughness
K _Q	-	critical value of K measured under conditions which cannot be demonstrated to meet all criteria for a valid K _{IC} test.
L	-	half-span of a beam in three point bending
M	-	bending moment
n	-	work hardening exponent in the Ramberg-Osgood power hardening law
p	-	used to denote load-control
P	-	force
r	-	distance ahead of a crack tip in r, θ polar co-ordinate system
ds	-	increment in the contour path

\mathbf{T}	=	the outward fraction vector on ds .
$\bar{\mathbf{u}}$	=	the displacement vector at ds
U	=	potential energy of a cracked body under load
\dot{v}	=	used to denote displacement control
V_{LL}	=	load-line-displacement
W	=	loading work per unit volume
n	=	constant in Ramberg-Osgood power hardening law
Γ	=	the path of the integral which encloses the crack tip
ϵ	=	strain
$\bar{\epsilon}_y$	=	yield strain
ϵ_{ij}	=	strain tensor
θ_T	=	$\theta_{el} + \theta_{pl}$ = total angular deflection of a beam
θ_{el}	=	elastic contribution to total angular deflection
θ_{pl}	=	plastic contribution to total angular deflection
θ	=	angular displacement ahead of a crack tip in r, θ polar coordinate system
λ	=	a parameter of value ≈ 1 for metals
ν	=	Poisson's ratio
σ	=	stress
$\bar{\sigma}_y$	=	yield stress
$\sigma_{0.2}$	=	0.2% proof stress
σ_{UTS}	=	ultimate tensile stress
σ_{eff}	=	$\frac{\sigma_{0.2} + \sigma_{UTS}}{2}$ = an effective yield stress
σ_{ij}	=	stress tensor
$\tilde{E}(\theta, n)$	=	non-dimensional function of θ and n

A COMPUTER-INTERACTIVE, SINGLE SPECIMEN

J-INTEGRAL FRACTURE TOUGHNESS TEST

1. INTRODUCTION

In the fields of engineering and materials science the concept of linear-elastic fracture mechanics is an accepted part of material testing. The use of plane strain fracture toughness as a material property is useful in engineering studies because it allows the prediction of critical crack sizes where the stresses in a body or structure are known. The measurement of plane strain fracture toughness, K_{IC} , is covered by ASTM Standard E 399 [1]. This test is relatively simple and, for the most part, easily understood. For plane strain fracture toughness to be measured in any test a most important criterion which must be met is that the specimen size be sufficiently large to ensure that plane strain conditions prevail across most of the specimen thickness. This means that there is a minimum specimen size for each material tested. Thus the specimen thickness and the crack length must both be greater than $2.5(K_{IC}/\sigma_{0.2})^2$, where K_{IC} is the measured plane strain fracture toughness and $\sigma_{0.2}$ is the 0.2% proof stress of the material.

In many instances materials are tested from parent bodies which do not allow specimens large enough for the measurement of K_{IC} to be taken from them. For example, some modern, large calibre gun barrels are of sufficiently high toughness that valid plane strain fracture toughness specimens cannot be taken from the walls of the gun tube. Tests using sub-sized specimens exhibit unacceptably high plasticity in their test records and hence alternative test techniques to the K_{IC} test method must be used. One method which admits a degree of plasticity is the J-integral test method which is covered by ASTM Standard E 813 [2]. The test method predicts a critical value of J at which the crack first begins to extend. By convention this critical value of J is denoted J_{IC} because the test is predominantly in mode I opening.

Under most circumstances the measurement of J_{IC} for a high toughness material (such as gun barrel steel) is an involved, multiple specimen test method because the critical value of J has to be inferred from the J-Aa behaviour obtained from a number of specimens. Aa is the increase

in crack length associated with each J measurement, and will be discussed in the following section. However, now that computer-interactive test machines are readily available to researchers it is possible to make use of the single specimen J-integral test method which utilizes unloading compliance measurements from which the extent of crack growth is inferred.

A short paper covering the initial development of the computer-interactive single specimen J-integral test method at MRL has been published [3]. The present work covers the same general aspects of the test method as [3] but expands considerably on details of computer programs and error analyses. This is facilitated by practical examples of the J-integral test using a gun barrel steel.

2. THE J-INTEGRAL

The development of the concept of the J-integral as a parameter which can describe the fracture toughness of a material is based on the demonstration that a path-independent integral, J [4], can uniquely describe the crack tip stress singularity in a material which obeys the Ramberg-Osgood power hardening law of deformation plasticity. This power hardening law for the case of simple tension can be stated,

$$\frac{\epsilon}{\bar{\epsilon}_y} = \frac{\sigma}{\bar{\sigma}_y} + \alpha \left\{ \frac{\sigma}{\bar{\sigma}_y} \right\}^n \quad (1)$$

where

- σ = stress
- ϵ = strain
- $\bar{\sigma}_y$ = the yield stress
- $\bar{\epsilon}_y$ = the yield strain, $\bar{\epsilon}_y = \bar{\sigma}_y/E$
- E = Young's modulus
- α = a material constant
- n = work hardening exponent

From the calculus of variations, Rice [5] showed that J, the path-independent integral, could be formulated,

$$J = \int_{\Gamma} (W dy - T \cdot (\partial \bar{u} / \partial x) ds) \quad (2)$$

where $T.(\partial \bar{u}/\partial x)$ = the rate of work input from the stress field into the area enclosed by Γ .

Γ = the path of the integral which encloses the crack tip.

W = loading work per unit volume.

ds = increment in the contour path.

T = the outward traction vector on ds .

\bar{u} = the displacement vector at ds .

J can also be interpreted as the change in the potential energy of a cracked body with a small increment in crack length [6].

Using the path independent characteristics of the J -integral, Rice and Rosengren [7] and Hutchinson [8a,b] showed that the following equations for the stresses and strains at the crack tip apply;

$$\sigma_{ij} = \bar{\sigma}_y \left[\frac{J}{\alpha \bar{\sigma}_y \bar{\epsilon}_y I_n r} \right]^{1/n+1} \tilde{\Sigma}_{ij}(\theta, n) \quad (3)$$

$$\epsilon_{ij} = \alpha \bar{\epsilon}_y \left[\frac{J}{\alpha \bar{\sigma}_y \bar{\epsilon}_y I_n r} \right]^{n/n+1} \tilde{E}_{ij}(\theta, n) \quad (4)$$

where $\bar{\sigma}_y$ = mean material yield stress

$\bar{\epsilon}_y$ = mean material yield strain

α = constant in the Ramberg-Osgood power hardening law

n = work hardening rate from the Ramberg-Osgood power hardening law.

I_n = coefficient of strain hardening stress intensity which has been evaluated numerically, [8a,b].

r, θ = polar co-ordinates.

and J can be evaluated for a boundary removed from the crack tip.

The similarities between the above formulations in terms of J and those in terms of K , the stress intensity factor [9], are readily apparent; see also Liu [10], and Figure 1 for a summary of the HRR model and the linear-elastic model of the stress-strain fields at the crack tip.

We see, above, that J can be used to describe the stress and strain singularities at the crack tip and, like K , J can be measured by a mechanical test, thus J can be evaluated physically as the change in potential energy, U , as the crack extends; see [11] and [12] for the following proof.

$$J = \left(\frac{\partial U}{\partial a} \right)_p \text{ and } J = - \left(\frac{\partial U}{\partial a} \right)_v \quad (5)$$

where p and v denote load and displacement control respectively. For the linear-elastic case we write:

$$J = \frac{1}{2} p \frac{\partial v}{\partial a} \text{ and } J = - \frac{1}{2} v \frac{\partial p}{\partial a} \quad (6)$$

and for the non-linear elastic case:

$$J = \int_0^p \left(\frac{\partial v}{\partial a} \right)_p dp \text{ and } J = - \int_0^v \left(\frac{\partial p}{\partial a} \right)_v dv \quad (7)$$

If we deal with deeply cracked beams we can write the above in terms of the deflections of the beam, where:

$$\theta_T = \theta_{el} + \theta_{pl} \quad (8)$$

where θ_T = total deflection
 θ_{el} = elastic contribution to total deflection
 θ_{pl} = plastic contribution to total deflection

When the ligament is fully plastic, $\theta_T \dot{=} \theta_{pl}$ and $\therefore \theta_T = v/L$ (9)

where v = back face displacement of the beam

L = 1/2 the loading span of the beam

$$\text{thus } \theta_{pl} = f\left(\frac{M}{Bb^2 \bar{\sigma}_y}, \frac{\bar{\sigma}_y}{E}, n\right) \quad (10)$$

$$\therefore M = Bb^2 \bar{\sigma}_y h \left(\theta_{pl}, \frac{\bar{\sigma}_y}{E}, n \right) \quad (11)$$

and $M = PL$

$$\text{thus } P = \frac{Bb^2}{L} \bar{\sigma}_y h \left(\frac{v}{L}, \frac{\bar{\sigma}_y}{E}, n \right) \quad (12)$$

$$\text{we know } \frac{\partial P}{\partial a} = - \frac{\partial P}{\partial b} = - \frac{2bB}{L} \bar{\sigma}_y h \left(\frac{v}{L}, \frac{\bar{\sigma}_y}{E}, n \right) \quad (13)$$

and substituting $L = \frac{M}{P}$ in (13) and (7)

$$J = \frac{2}{b} \int_0^v P dv \quad (14)$$

we note that $\int_0^v P dv$ is the area, A , under the load/load-point-displacement curve for the beam.

Equation 14 is the fundamental relationship which is used for the evaluation of J for small increments of crack length. This is used in the present ASTM standard for the measurement of J_{IC} [2].

There are two methods by which J can be measured, one using a multiple specimen technique where a series of specimens is tested covering a range of crack increments and the other using a single specimen where the length of the crack is continuously monitored as it extends during a test. The J -integral value is determined from the area under the load/load-line-displacement record using equation 14 above. This method is summarized diagrammatically in Figure 2. Both methods lead to the measurement of a J - A_a curve. This curve, in itself, does not determine the critical value of J , J_c , where the crack begins to extend. This is done by linearly back-extrapolating the J - A_a data to the "blunting line". The blunting line describes the apparent crack growth which occurs as the crack tip blunts during the initial development of the plastic zone. The blunting line is derived from the relation given by Rice and Johnson [13] where:

$$J = \lambda \sigma_{eff} CTOD \quad (15)$$

where $\lambda \approx 1$ for metals

σ_{eff} = effective yield strength of the material

CTOD = crack tip opening displacement.

The effective increment in the position of the crack tip, Δa , can be considered to be about $0.5 \times \text{CTOD}$ and hence a simple relation for this blunting line can be written

$$J = 2 \times \sigma_{eff} \times \Delta a \quad (16)$$

where σ_{eff} is often defined as $\left(\frac{\sigma_{0.2} + \sigma_{UTS}}{2} \right)^*$

The point where the linear regression line through all admissible J- Δa data pairs [2] intersects the blunting line is considered to be the critical value of J at which the crack first extends.

What constitutes admissible J- Δa pairs is discussed in detail in [2].

The computer-interactive, single specimen J-integral test method described in the following sections permits the measurement of J_{IC} in accordance with the ASTM standard [2].

3. THE OBJECTIVES OF THE DEVELOPMENT OF THE COMPUTER-INTERACTIVE, SINGLE SPECIMEN J-INTEGRAL TEST METHOD

When all refinements are completed, (and this can only be achieved by the continued use of the test method developed here), the test method should permit the determination of J_{IC} , i.e. fracture toughness, on a routine basis and in accordance with ASTM E 813 [2].

The objectives of the development of the computer-interactive single specimen J-integral test method are:

* The ASTM Standard, [2], suggests that "when estimating σ_{eff} influences of testing conditions such as loading rate and temperature should be considered".

- (1) Accurately determine J_{IC} .
- (2) Document all relevant calculations,
- (3) Store all test data in a logical and retrievable form,
- (4) Be flexible in a mathematical sense to allow compliance calibrations, Young's modulus, Merkle-Corten coefficient and other test parameters to be inserted into the program or readily changed,
- (5) Ability to re-examine test data.

Due to the limited transient programming area (TPA) of 32 K words available in the PDP11/04 computer at the time of the development of the program for the control of the J-integral test, the program may be regarded as incomplete because it does not undertake the linear regression through the J-A test data to the blunting line for the calculation of J_{IC} . This can be done using a plotting file created for this purpose.*

The objectives (1)-(4) are met by the current J-test program for the PDP11/04; JCTS.BAS, for the compact tension specimens. Objective 5 is met by programs written for both the VAX11/780 and the PDP11/04 which allow files written by the PDP11/04 under RT11 version 4.1 to be treated as data files for what is effectively another J-integral test. This program, JRERUN.BAS, re-examines the existing data but allows the insertion of accurate specimen dimensions and crack lengths and the use of alternative compliance calibrations in the calculations. Estimates of the accuracy of the linear regression analysis to infer crack-length are made by this program.

The programs are listed in Appendix 1 and details of these programs are given later in this report.

4. THE J-INTEGRAL TEST SPECIMENS

The present work was mainly undertaken for the "compact tension" specimen design and although the test method is readily applicable to beam specimens, it is not dealt with in detail in this report.

* This feature will be incorporated in the program when the computer is upgraded to a PDP11/34 which has a larger TPA.

Several specimen designs have been proposed for the compact tension specimen for J-integral testing [14]. The primary requirement from the specimen is the need for the measurement of the load-line-displacement, see equation 14 above.

For J-integral testing the present work used a modified compact tension specimen which conforms to the ASTM E 399 specimen geometry except that it has an integral knife edge machined at the load-line, see Figure 3. This specimen is similar to that proposed by Clarke et al [14], except that the pin holes are closer together. The advantage of utilizing specimens which are essentially common to the E 399 and E 813 test methods is that, where K_{Ic} cannot be measured, the specimens are readily converted to J-integral specimens. The MRL specimen design would probably preclude the use of clevises with roller bearings, however, there is no conclusive evidence that this is a necessary feature of J-integral tests using the compact tension specimen.

The J-integral specimen manufactured by MRL is designated MRL J03, [15].*

5. THE COMPLIANCE CALIBRATION FOR THE COMPACT TENSION J-INTEGRAL SPECIMENS

At the present time there are two elastic unloading compliance calibrations which are immediately applicable to the MRL J03 specimen. The first is an experimental unloading calibration using 13 mm thick MRL J03 specimens [16], and the second a theoretical compliance calibration developed from a finite element program, PAFEC, run on a VAX 11/780 computer [17a,b]. These compliance calibrations are plotted in Figures 4 and 5 together with the unloading compliance calibrations supplied in ASTM E 813 (see also Saxena and Hudak [18] and Newman [19]). These calibrations are used in Section 8 of this work. Listings of the compliance data for compact tension specimen designs are given in Appendix 2.

* This is a specific designation. The "03" refers to an a/W of 0.3. Other starter crack lengths can be used.

6. THE HARDWARE FOR THE COMPUTER-INTERACTIVE

SINGLE SPECIMEN J_{IC} TEST

The single specimen J-integral tests were undertaken on a 250 kN servohydraulic testing machine (MTS 810 system), interactive with a PDP11/04 computer.*

The graph generated by the program, J-4a, was plotted on a Tektronix 4010-1 VDU and dumped via a Tektronix thermal imager while the analogue output of load/load-line-displacement was plotted using a HP 7090A plotter. This plotter can be controlled by the PDP11 and hence could be used for the re-plotting of the data as stored by the program. More conveniently this is handled via the VAX11/780 and appropriate graphics terminals.

The load-line-displacement was measured using an MTS 632.02C.20 clip gauge. The locating edges on the clip gauge arms were modified slightly to accommodate the MRL J03 integral knife edge design. The linearity and reproducibility of this clip gauge were tested experimentally and the data plotted in Figure 6. It was considered unnecessary to use any correction factors over the range used for the J-integral test of an MRL J03 specimen.

7. THE SOFTWARE FOR THE COMPUTER-INTERACTIVE

SINGLE SPECIMEN J-INTEGRAL TEST

The software written for the single specimen J-integral test method and the data analysis programs are largely interactive and self explanatory, however brief descriptions of the programs are given in Appendix 3. Some documentation of the variables in the control program for the PDP 11/04, where relevant to the description of the software in this section, is given in Appendix 4.

The programs which undertake J-integral testing and data analysis are in two separate suites.

- (1) The computer-interactive control program written for the PDP 11/04.
- and
- (2) The data analysis programs written for the VAX11/780 and PDP11/04 which utilize the data generated and stored on disc by the control program.

* This computer has a TPA of 32K words but is to be upgraded to a PDP11/34 with a TPA of 64K words.

7.1 The control program on the PDP11/04-MTS 810

The language used for the control program is DEC Multi-user BASIC with MTS and Tektronix enhancements for the Master Segment Generator and the graphics respectively [20a,b]. The Master Segment Generator (MSG) is used to generate, through a D/A converter, the offset signal to drive the servo-valve.

The single specimen J-integral test is conducted in stroke control, with the position of the ram being measured by its displacement transducer rather than using the displacement of the specimen as measured by the clip gauge. This makes the test fail safe should the clip gauge signal fail.

At the present time, for J-integral tests using the MRL J03 specimens, ± 2047 bits = ± 5 mm of ram travel. This stroke can be decreased to allow an increase in the number of data points acquired for any test using J03 specimens. Incrementing the stroke during the test results in a small increment in the load applied to the specimen, while displacement in the load-line of the notch is measured by the clip gauge where ± 2047 bits = ± 2 mm. For the MRL J03 specimen it is found that 2 mm movement of the clip gauge is ample for most J-integral tests. This calibration can be altered using the MTS 440.21 signal conditioner to increase the sensitivity of the test.

The software for the test method is summarised in the flow diagram, Figure 7.

The single specimen J-integral test method requires the collection of load/load-line-displacement data for each bit-wise increment (or decrement in the case of an unloading) produced by the Master Segment Generator, (MSG). Each bit-wise increment and decrement in stroke is accompanied by the sequential reading number and with each reading is recorded load, load-line-displacement, cumulative area under the load/displacement record and a switching integer (Z9), which has a value of 1,2,3, or 4 depending on the call to the MSG, i.e. the ramp control. These data are written sequentially into a large virtual file on disc as binary numbers. The switch, Z9, is the integer used to control the loading and the unloading sequences of the test and is incorporated in an "ON GOTO" statement to call the bit-wise output from the MSG, see Figure 7. The ramp control is shown schematically in Figure 8. The switch has an important secondary function in the JRERUN.BAS programs on the VAX11/780 and PDP 11/04 where this record is used to control the use of the load/load-line-displacement data in a manner analogous to the control program on the PDP11/04, viz., the switch designates data which are to be treated as unloading data for inferring crack length via the unloading compliance and the normalized compliance/normalized cracklength calibration such as those in Figures 3 and 4. JRERUN.BAS is discussed in detail in section 7.2.

The acquisition of the load/load-line-displacement data is undertaken as a separate (but common) subroutine (through a "GOSUB" statement) called by each of the ramp routines set by the ramp switch, i.e. the acquisition of data is always undertaken in the same manner. Thus, for each sequential bit-wise increment or decrement in stroke from the MSG, when the ram of the MTS has stopped moving, ten reading pairs of load and load-line-displacement are taken at 1 millisecond intervals and then averaged. These

average values are "written" into the record and used for the calculation of the cumulative area under the load/displacement curve. Once all calculations have been completed the ramp is re-activated, see Figure 8.

Initially the test behaves in a linear-elastic manner. A load, P_7 , to which the specimen can be loaded and still remain linear-elastic is used to establish that the area calculation is correct. This is done by comparing the cumulative area up to this elastic load with a geometric calculation using the slope of the linear-elastic loading line and the elastic load; viz. the area of a triangle. In the linear-elastic region the cumulative area should be to within +2% of the geometric calculation.

The test parameters such as specimen dimensions, Young's modulus, elastic load for preliminary calculations, Merkle-Corten coefficients [21] and the load cell calibration are inserted into the computer and also stored in the data file ("name".DAT) at the start of the test. A plotting file ("name".PLT) is also set-up concurrently with the data file. The graphics for the J-Aa plot are also set-up before the test. The test starts with an initial loading in the linear-elastic range, the limit set by the elastic load (Z9=1), and the area calculation is checked as described above. After a 20 bit increment in stroke when Z9=2 (see next paragraph), a 10% unloading (Z9=3) allows the initial crack length (a_0) to be established from the unloading compliance calibration in the program.* To produce crack growth in a controlled way the bit-wise increment in stroke (Z9=2) is limited to a pre-set number of bits from the MSG. This can be changed readily within the program but for a compact tension specimen geometry such as the MRL J03 it has been found that 20 bits total output from the MSG for each loading ramp is sufficient to produce measurable crack extension. As the stroke is increased the cumulative area under the load/displacement curve is "written" into the data and plotting files (VF1 and VF2 respectively). On attaining the total number of bits of stroke increment the specimen is unloaded (Z9=3) to 90% of the load in the preceding loading ramp and, using a linear regression analysis on the data, the unloading compliance is calculated and normalized with respect to E (Young's modulus) and B (specimen thickness). No area under the curve is calculated in this section of the program. Through the compliance calibration in the program (see Section 5), crack length is inferred and the corresponding J-integral value calculated using equation 14. A summary of these results is "written" into the plotting file (VF2). The J-integral test then continues, firstly by restoring the specimen to the displacement at the top of the unloading (Z9=4) and then by bit-wise incrementing the stroke a further 20 bits (Z9=2) to promote further crack growth. The determination of the area under the load/displacement curve is resumed at the point in the program when Z9=2.

* It has been found that a_0 is often better estimated if this first 10% unload is used for the calculation rather than the initial elastic loading as specified in [2]. This unloading must occur in the linear-elastic regime.

The data "written" into the virtual files (VF1 and VF2) can be retrieved using the program ACCESS.BAS." All details of the test including scaling factors are included in the printout of data from the PDP11/04 virtual files.

A typical analogue output from a single specimen J-integral test is given in Figure 9; this will be dealt with in detail in Section 8 when the test results from gun steel are discussed.

7.2 The data analysis programs on the VAX11/780 and PDP11/04

The main program in this suite of programs for the VAX11/780 and PDP11/04 is for the re-analysis of the test data for the purpose of arithmetic checks and the use of alternative calibrations or test details such as specimen dimensions etc. To use this program on the VAX the data file used by the JRERUN.BAS program must be in ASCII code. The data file created on the PDP11/04 and loaded into the VAX11/780 is in binary numbers and must therefore be re-written in ASCII code. This is achieved by a small program to create an ASCII code output file which can be utilised by the data analysis programs (see Appendix 2 for details). In the case of JRERUN.BAS for the PDP 11/04 the virtual files are read directly. In all other respects the programs are similar.

The data analysis program, JRERUN.BAS requires specimen details to be input again (should errors be discovered in the original measurement of the specimen) and also, with the accurate measurement of initial crack length now that the test specimen has been broken open after heat tinting, a correct value of the Merkle-Corten coefficient can be inserted for compact tension J tests. Similarly Young's modulus can be changed for the re-analysis of the test data. Most importantly, however, alternative compliance calibrations can be used if they are available for the specimen geometry tested. This should allow the eventual attainment of better correspondence between measured crack length values and those inferred by the unloading compliance technique. The standard, ASTM E 813 [2], requires "that the final crack extension value, as predicted by single-specimen techniques, must agree with the averaged heat tint values within 15%". Using the present re-analysis method this requirement can usually be met for the compact tension J-integral specimen (see Section 9). The JRERUN.BAS program also gives the correlation coefficients for linear regression analysis of the unloading data and also permits the examination of the load/load-line-displacement data pairs to decide if any should be discarded from the start of the unloading to allow for non-linear effects. Some computer-interactive J-integral test programs use a delay before an unloading to reduce non-linear effects and time-dependent, plastic recovery [22,23]. The control program on the PDP11/04 overcomes non-linear effects to some extent by discarding a fixed number of data points for the linear regression to establish the compliance. The data analysis program on the other hand allows the number of points which are discarded to be varied at each unloading.

The program prints a summary of all calculations together with all test details including the compliance calibration used to infer the crack extension in the J-integral test.

Another program, ACCESS1.BAS, for the VAX only, is a simple utility to allow the examination of any part of the load/load-line-displacement record (stored as load/load-line-displacement data pairs). This program "writes" a simple plotting file which can be used with MRL utility program GRAPH [24] so that the record between any two reading numbers can be replotted. The ACCESS1.BAS/GRAPH combination can be used to examine for any hysteresis in the unloading/reloading sequence and to obtain the slope of any unloading or reloading part of the record, should this be necessary (see Section 10).

8. COMPUTER-INTERACTIVE, SINGLE SPECIMEN J-INTEGRAL TESTS AND A MULTIPLE SPECIMEN J-INTEGRAL TEST ON A NI-CR-MO GUN STEEL

The material used in this work was taken as MRL J03 compact tension specimens in the transverse orientation from a 4.5 inch Naval gun.* This material was used for the preliminary investigation of the J-integral test method [3] because limited fracture toughness data was available for this steel [25,26]. The chemical composition of the steel is given in Table 1.

A micrograph of the steel, with orientation transverse to the barrel wall, is shown in Figure 10.

The mechanical properties of this gun steel have been reported in earlier work [25] and are summarised in Table 2. Estimates of fracture toughness, using ASTM E 399 [1], were made from the load/displacement records of tests on the steel [26]; these are reproduced in reference 25. It should be noted, however, that the fracture toughness values reported in Table 2 are designated as K_Q values because the fracture toughness tests were invalid [26]. For the 51 mm thick compact 'C'-shaped specimens (51CC) and the 51 mm thick compact tension specimens (51CT) the P_{max}/P_5 ratios were approximately 1.12. It is considered, therefore, that the K_Q values reported in Table 2 approach the K_{Ic} of the material. Thus in the transverse orientation K_{Ic} is approximately $130 \text{ MN m}^{-3/2}$.

* MRL Reference, Barrel G1 (1971).

TABLE 1

Chemical Composition of Steel from a 4.5 inch Naval Gun
(wt%)

C	Mn	P	S	Si	Ni	Cr	Mo
0.32	0.62	0.009	0.011	0.20	2.56	0.84	0.57

TABLE 2

Mechanical Properties of Gun Steel

$\sigma_{0.2}$	791 MN m^{-2}
σ_{UTS}	932 MN m^{-2}
K_Q 25CT (transverse)	$133 \text{ MN m}^{-3/2}$
K_Q 51CC (transverse)	$130 \text{ MN m}^{-3/2}$
K_Q 51CT (longitudinal)	$150 \text{ MN m}^{-3/2}$ (160 $\text{MN m}^{-3/2}$ est. from COD)

Note: All properties are measured at 20°C.

Using the computer-interactive test method described above, a series of standard, single specimen J-integral tests conforming to ASTM E 813 [2] was undertaken and the inferred and measured crack length data obtained from each test are given in Tables 3a and b. Table 3a summarizes the results from the actual test as controlled by the program on the PDP11/04, and this program incorporated the unloading compliance obtained using the finite element program, PAFEC, [17a,b] (see Figure 4). Table 3b summarizes the results from a re-run of the experimental data using JRRUN.BAS on the VAX 11/780. Errors in the measurement of a_0 , a_f and Δa are given in both tables.

TABLE 3a

Summary of J-Integral Test Data using PAFEC-Generated Compliance Calibration.
Data from PDP11/04 Control Program, ⁽¹⁾ (JCTS.BAS)

Specimen No.	a_o		Err% ⁽²⁾	a_f		Err%	Δa		Err%
	meas. mm	compl. mm		meas. mm	compl. mm		meas. mm	compl. mm	
B1	30.14	30.74	+2.0	31.52	31.77	+0.88	1.38	1.03	-25.4
B2	30.43	31.07	+2.1	31.08	31.61	+1.7	0.65	0.54	-16.9
B3	30.09	30.53	+1.5	31.38	31.76	+1.2	1.29	1.23	-4.7
B4	30.18	30.75	+1.9	30.47	31.01	+1.8	0.29	0.26	-10.3
B6	30.50	31.00	+1.6	31.13	31.58	+1.4	0.63	0.58	-7.9
B8	29.94	30.92	+3.3	-	31.04	-	-	0.12	-
B9 ⁽³⁾	30.16	31.18	+3.4	-	30.60	-	-	0.0	-
B10 ⁽³⁾	30.19	30.69	+1.7	30.78	31.18	+1.3	0.59	0.49	-16.9
B11	30.27	30.47	+0.7	30.40	30.60	+0.7	0.13	0.13	+0.0

Note:

- (1) Young's modulus = 203 GPa, used in preliminary calculations.
- (2) Err% is defined here as the error in the value inferred from the unloading compliance calibration.

$$\text{Err\%} = \frac{X_{\text{inferred}} - X_{\text{measured}}}{X_{\text{measured}}} \times 100$$

X_{measured} is taken as absolutely correct. It is only subject to errors in physical measurement and this can be demonstrated to be $\pm .01$ mm (± 10 μ m).

- (3) No heat tinting results available for specimens B8 and B9.

TABLE 3b

Summary of J-Integral Test Data using an Experimental Compliance Calibration.
Data from VAX11/780 Computer Program, (JRERUN.BAS)

Specimen No.	a_o meas. compl. mm mm		Err% ⁽¹⁾	a_f meas. compl. mm mm		Err%	Δa meas. compl. mm mm		Err%
B1	30.14	29.76 ⁽²⁾	-1.3	31.52	30.94 ⁽⁴⁾	-1.8	1.38	1.18	-14.5
		30.07 ⁽³⁾	-0.2		31.22	-1.0		1.15	-16.7
B2	30.43	30.09	-1.2	31.08	30.68	-1.3	0.65	0.60	-7.7
		30.38	-0.2		30.97	-0.4		0.59	-9.2
B3	30.09	29.54	-1.8	31.38	30.77	-1.9	1.29	1.23	-4.7
		29.86	-0.8		31.06	-1.0		1.20	-7.0
B4	30.18	29.79	-1.3	30.47	30.07	-1.3	0.29	0.28	-3.4
		30.10	-0.3		30.37	-0.3		0.27	-6.9
B6	30.50	30.04	-1.5	31.13	30.65	-1.5	0.63	0.61	-3.2
		30.35	-0.5		30.94	-0.6		0.59	-6.3
B8 ⁽⁵⁾	29.94	29.96	+0.1	-	30.08	-	-	0.12	-
		30.27	+1.1		30.39	-		0.12	-
B9 ⁽⁵⁾	30.16	29.72	-1.5	-	29.72 ⁽⁶⁾	-	0.07 ⁽⁶⁾	0.00	-
		30.04	0.4		30.04 ⁽⁶⁾	-		0.00	-
B10	30.19	29.76	-1.4	30.78	30.27	-1.7	0.59	0.51	-13.6
		30.07	-0.0		30.57	-0.7		0.50	-15.3
B11	30.27	29.51	-2.5	30.40	29.64	-2.5	0.13	0.13	0.0
		29.81	-1.5		29.94	-1.5		0.13	0.0

(1) Err% as defined for Table 3a.

(2) Upper line are results calculated using Young's modulus = 203 GPa.

(3) Lower line are results calculated using Young's modulus = 210 GPa

(4) This value is not the same as that given in Table 3 of [3], because in the present analysis the "next-to-final" unloading data pairs were used for linear regression analysis. More unloading data pairs are available and hence the estimate of Δa is possibly more accurate than in [3] despite the fact that a small amount of crack growth has occurred between unloads.

(5) No heat tinting results available for specimens B8 and B9.

(6) B9 showed no crack growth.

For specimens B1 to B11 different final crack extension values were attained for each individual test which means, therefore, that the series could also be treated as one multiple specimen J test. The final crack length for each of the tests was marked by heat tinting; some of the tinted specimens are shown in Figure 11. The final Δa values measured from the heat tinted specimens are included in the summary of the test results given in Tables 3a and b and were measured using an unweighted 11 point average* which included the two outer-surface locations. In some cases, where the final crack extensions are quite small, less than 0.20 mm, it is possible that the requirements for a valid (or even useful) J-integral test are not met (see [2] section 9.3).

From Table 3a it can be seen that the original PAFEC-generated compliance calibration used in the PDP11/04 control program gives what appears to be good estimates of a_0 and a_f , with maximum errors of up to +3.4%. Further, the PAFEC compliance calibration results in consistent over-estimates of actual crack-length; thus the relative errors between any sets of a_0 and a_f values are apparently very small. However the calculations of Δa (which use a_0 and a_f values) are often subject to very large errors; indeed many of the estimates of crack extension using the present PAFEC compliance calibration do not meet the requirements of the ASTM standard for the J-integral test [2] where "the final crack extension value, as predicted by single specimen techniques, must agree with the averaged heat tint value within 15%". There are two possible reasons for this; (1) that the compliance calibration used initially in the control program on the PDP11/04 is not entirely appropriate for the test and (2) the number of points discarded from the start of the unloading for the linear regression analysis is not sufficient to avoid all non-linear behaviour. This program originally discarded 2 unloading data pairs. These data can be re-analysed, however, using alternative compliance calibrations and varying the number of discarded data pairs.

Using the program JRERUN.BAS on the VAX11/780 (or PDP11/04) an alternative compliance calibration is tested. The only other compliance calibration presently available for the MRL J03 specimen is the experimental unloading compliance calibration generated using 13 mm thick MRL J03 specimens [16], see Figure 4. Using this alternative calibration, and discarding 4 data points from the start of the unloading, gives slightly different estimates of a_0 and a_f ; the results of the calculations are summarized in Table 3b.

The experimental compliance [16] tends to slightly under-estimate the values of crack lengths and this can be altered further by using a higher value of Young's modulus, although the value for the gun steel used in the present work has not been measured. A Young's modulus value of 203 GPa was

* It should be noted that ASTM E 813 uses nine inner points plus a weighted two outer points for the calculation of mean crack length. The present unweighted 11 point average appears to give better correspondence with crack length inferred from compliance than the 9 + 2 point average used in E 813.

used for the normalization of the data in the experimental determination of the unloading compliance calibration but a value of 210 GPa may be more appropriate for the thick specimens used in the J-integral testing of specimens B1-B11. Both Young's modulus values are used for the calculations presented in Table 3b. While an E value of 210 GPa appears to give a closer correspondence with the heat tinting data there is a greater relative error between a_o and a_f values using this higher E and, as a result, slightly larger errors in the estimations of the Δa values. Over-all the use of the experimental unloading compliance data [16] in the J-integral test offers a better correspondence (smaller Err% values) between the inferred crack length values and those measured from heat tinted specimens than is achieved using the original PAFEC-generated unloading compliance calibration.

Typical J- Δa plots for the single specimen test methods are shown in Figures 12, 13 and 14. These plots used J- Δa data pairs generated by JRRUN.BAS on the VAX11/780.

The blunting line used in all calculations is given by equation 16, and is included on all J- Δa plots.

As mentioned above, the series of specimens B1 to B11 can also be treated as one multiple specimen J-integral test on this gun barrel steel. The a_f values used in this method are those obtained from the heat tinting experiments and the J values corresponding to each final Δa value were calculated from the area under the load/load-line-displacement record at the start of the final unload of each test. The J- Δa plot for these data is shown in Figure 15.

An estimate of fracture toughness in terms of stress-intensity factor, K, is made using the relation

$$K_{Jc} = \sqrt{E' J_{Ic}} \quad (17)$$

- where
- K_{Jc} = the fracture toughness derived from a multiple specimen or single specimen J-integral fracture toughness test.
 - J_{Ic} = value of J at the intersection of the blunting line and the linear regression through admissible J- Δa data points.
 - E' = the value of Young's modulus used in unloading compliance calculations. In the cases of relatively thick specimens this E' value would approach $E/(1-\nu^2)$, where ν is Poisson's Ratio.

The following table summarizes the results of the J-integral calculations using both multiple and single specimen test methods.

TABLE 4

Summary of J-Integral Test Results for a NiCrMo
Gun Steel at 20°C

Specimen No.	$J_{IC}(1)$ kNm^{-1}	$K_{JC}(1)$ $MNm^{-3/2}$	$\Delta a_{max}(1)$ mm	$J_{IC}(2)$ kNm^{-1}	$K_{JC}(2)$ $MNm^{-3/2}$	$\Delta a_{max}(2)$ mm	$\Delta a_{max}(\text{measured})$ mm
B1	80	127.4	1.04	73	121.6	1.18	1.38
B2	96	139.6	0.54	78	126.2	0.61	0.66
B3	85	131.3	1.23	80	127.5	1.23	1.30
B4	45	95.6	0.26	84	130.4	0.26	0.30
B6	80	127.4	0.60	76	124.2	0.60	0.64
B8 ⁽³⁾	78	125.6	0.12	71	120.3	0.12	-
B9 ⁽³⁾	>60	-	0	>60	-	> 0	0.0
B10	58	103.3	0.49	57	108	0.51	0.60
B11	>61	-	0.13	>70	-	0.13	0.13
121.5 ± 15.9				122.6 ± 7.3			
Multiple Specimen ⁽⁴⁾ $J_{IC} = 93 \text{ kN/m}$ $K_{JC} = 137.4 \text{ MNm}^{-3/2}$							

Notes:

- (1) From the original PDP11/04 data, see [3]. 2 discards from the start of an unloading; PAFEC-generated unloading compliance calibration; $E = 203 \text{ GPa}$ and a Merkle-Corten Coeff of 2.265, (too high).
- (2) From JRERUN.BAS on the VAX 11/780. 4 discards from the start of an unloading; experimentally determined unloading compliance calibration; $E = 203 \text{ GPa}$ and a Merkle-Corten Coeff of 2.216, (correct value).
- (3) No heat tinting results for these specimens.
- (4) All data for $\Delta a_{max, meas}$ (viz B1, B2, B3, B4, B6, B9 ($\Delta a=0$), B10, B11).

The results of the calculations of J_{IC} , given in Table 4, for two methods of analysis show that the control program, JCTS.BAS and the arithmetically more accurate JRERUN.BAS produce similar J_{IC} values. Some tests such as B9 and B10 give measurably lower J_{IC} values than the remaining bulk of the tests. The reason for this is not apparent because the same test method and data analysis was applied to these specimens, and hence it must be concluded that specimens B9 and B10 are representative of the lower toughness values in what may be normal scatter for this material, viz. $K_{JC} = 122.6 \pm 7.3 \text{ MN m}^{-3/2}$.

From the results summarized in Table 4 it can be seen that the multiple specimen test gives a higher J_{IC} value than the series consisting of single specimen tests. This difference arises because of distribution of the J-Aa data points between the 0.15 and 1.50 mm exclusion lines. The multiple specimen test has these points evenly distributed between the exclusion lines, but in the cases of the single-specimen tests these data are often closer to the blunting line, thus producing lower J_{IC} values. Despite limited multiple specimen J-integral data both the single specimen and multiple specimen K_{JC} values agree well with the known K_Q values of the gun steel. Unfortunately, there are no K_{IC} values, but because the P_{max}/P_5 values for the test are approximately 1.12 [26], then the comparison between the K_{JC} values measured in the present work and the known K_Q values is not unreasonable.

These preliminary J_{IC} tests using the gun steel highlight some deficiencies in the computer-interactive single specimen J-integral test method, but these can be overcome by the use of JRERUN.BAS. The first deficiency is that JCTS.BAS should discard more than two unloading data pairs for the linear-regression analysis since there is evidence of non-linear behaviour within the first four data pairs. This contributes to errors in crack length measurement, although this would not readily be apparent in the "rounding off" of data to 2 decimal points. Another deficiency is that within JCTS.BAS the correlation coefficient for the linear regression analysis should be calculated and documented.* At the present stage of development this is only handled by JRERUN.BAS. A further limitation of the JCTS.BAS program is its lack of generality; certain lines within the program have to be edited if test parameters are changed; e.g. discards of data pairs in the linear regression, compliance calibration and displacement calibration. At a later stage of development the program could be expanded for these to be written into the program interactively.

Those factors which influence the accuracy of the measurements and calculations are discussed in Section 10.

* Limited TPA of PDP 11/04 does not permit these calculations to be undertaken.

9. FURTHER APPLICATIONS OF THE COMPUTER-INTERACTIVE, SINGLE SPECIMEN J-INTEGRAL TEST METHOD

At its present level of development this test method has been used for the measurement of the fracture toughness, J_{IC} , of 6 mm thick MRL J03 specimens of a precipitation hardened martensitic stainless steel, STA60, [27]. The results presented in [27] were found to behave similarly to those data reported for 17/4 PH, [22]. The greatest difficulty encountered with the test method was that the unloading compliance calibrations used in the work, PAFEC-generated in JCTS.BAS and experimentally measured in JRERUN.BAS, could not accommodate the large degree of crack tunnelling which occurred in the testing of the STA60. This problem is one which has not been addressed by the developers of unloading compliance J-integral test methods.

A second application of the computer-interactive, single specimen J-integral test method was in the measurement of the fracture toughness, J_{IC} , of a 105 mm gun tube (non-autofrettaged) of NiCrMo steel. In this work [28] it was possible to determine the plane-strain fracture toughness, K_{IC} , of the steel, with which to compare the J_{IC} value obtained from JCTS.BAS, as K_{JC} . The agreement between K_{IC} and K_{JC} was particularly good. Crack tunnelling in this series of tests was minimal, and hence agreement between inferred and measured A_a values generally conformed to ASTM E 813 [2].

These applications of the computer-interactive, single specimen J-integral test method have demonstrated its suitability for the testing of high strength steels.

10. DISCUSSION

The limited TPA of the PDP11/04 used in the present experiments meant that error and accuracy checks as specified in [2] could not be undertaken during the test. Thus most of the accuracy checks have to be undertaken retrospectively using the JRERUN.BAS program and this makes the J-integral test method developed in this work similar to the K_{IC} test [1], where a completed test can be declared invalid on the basis of retrospective analysis.

The standard [2] requires that the initial linear-elastic slope be used as a guide for the accuracy of the initial test set-up. If the PDP11/04 control program were to check the loading compliance following the elastic load-up ($Z_9=1$), then it would be essential for the elastic load limit of the test to be set to the maximum final pre-cracking load of the specimen. This means that if the test were found to be progressing incorrectly then it could be stopped and re-started without the need for further pre-cracking, i.e. the specimen would still satisfy the final pre-cracking requirements for a valid test. Unfortunately, this load is relatively low. For example, in the case of the gun steel (Section 8) the elastic load limit would be 25 kN or lower!

In the present method the specimens are checked for dimensional accuracy and so it can be assumed that if the clip gauge seats correctly in the specimen then errors in the load/load-line-displacement record will be minimal. (Correct seating of the clip gauge can be checked using very small pre-loads and unloads.) The alignment of the test machine is also checked prior to starting a series of J-tests. It is considered, therefore, that the preliminary check of the compliance is not necessary. Any discrepancies in compliance with the experimentally-determined value can probably be accommodated by small changes in Young's modulus in JRRUN.BAS (see below). This check of the initial linear elastic compliance is done indirectly by the JRRUN.BAS program. It can be shown that a $\pm 7\%$ variation in normalized compliance at $a/W = 0.60$ produces a $\pm 2.3\%$ variation in inferred a/W value, or, for a 25 mm thick specimen, a crack length of $30.60 \text{ mm} \pm 0.70 \text{ mm}$. With the exception of specimens B8 and B9, the initial crack length estimates in Table 3(a) fall within this range suggesting that most tests were correctly set-up.

The area calculation check in the linear-elastic loading region is considered more important than the linear-elastic loading compliance (above) because it will give an indication of the errors in the area under the load/displacement curve introduced by the area calculation. This can be checked further against the analogue plot (see below). To undertake this numerical check, it is desirable that the elastic load limit, P7, be set as high as possible at the start of the test so that a relatively large area is measured and checked against a calculated area (area of a triangle in the elastic region). In the present form of the test control program this elastic load limit is usually set higher than the maximum fatigue load (for the final 7.6 mm of crack growth) and this precludes the re-use of the specimen if a test does not proceed for any reason. Experience with steels has shown, however, that with the present instrumentation and level of development of the test method, preliminary compliance checks are unnecessary, and that once started the test should not be interrupted. The preliminary J-integral tests conducted on the gun steel revealed a slight error in the calculation of the area under the load/load-line-displacement record, producing an over-estimate of this area in the linear elastic region up to load P7 (see Table 5 below). This has been modified and now most MRL J03 specimens give an error in the elastic region of less than $+2.0\%$ [27,28]. The magnitude of error is calculated by the ACCESS.BAS program on the PDP 11/04. This particular error check gives a good indication of the accuracy of the area measurement in the initial stages of the test where, because of the slope of the load/load-line-displacement record, the calculation errors should be the largest of the test. This may also give a measure of the non-linearity which is observed at the start of most fracture toughness tests.

A check against the area under the analogue load/load-line-displacement records for specimens B1-B11, using a Kontron Bildanalyse Mini-MOP for area determination, shows good agreement between the calculated and measured areas. These are summarized in Table 5. It is not possible to determine errors for the computer-calculated areas because there are no measured areas which are absolutely correct. The areas measured from the analogue plots are subject to undetermined errors (but which are likely to be small anyway). These are, for example, the accuracy of the analogue plot (pen thickness, linearity of scales calibration, etc.) and the accuracy of usage of the Mini-MOP, see Table 5. Within these limitations, the agreement

between the calculated and the measured areas for specimens B1-B11 demonstrates that the JCTS.BAS program produces acceptable estimates of area under the load/load-line-displacement record from which J values can be determined.

TABLE 5

Area Calculations for Single Specimen J-Integral Tests

Specimen No.	Measured Area ⁽¹⁾ kN mm	Calculated Area kN mm	Error to Elastic ⁽²⁾ Load Limit %	Elastic Load Limit kN
B1	35.97 ± 0.233	34.92	1.58	35
B2	32.07 ± 0.035	32.68	2.31	35
B3	39.84 ± 0.093	39.14	4.60	35
B4	23.20 ± 0.066	23.63	2.45	35
B6	27.07 ± 0.072	27.21	2.05	35
B8	18.42 ± 0.060	19.51	4.11	35
B9	13.90 ± 0.037	19.25	3.54	30
B10	29.71 ± 0.032	29.97	1.21	35
B11	19.85 ± 0.052	18.82	2.48	35

Notes:

(1) Measured using Mini-MOP; standard deviations reflect reproducibility of area measurements using a minimum of 4 determinations.

(2)
$$\text{Err\%} = \frac{A_{\text{measured}} - A_{\text{calc}}}{A_{\text{calc}}} \times 100;$$
 results from ACCESS.BAS.

One limitation of the test procedure at the present level of development is in the limited number of load/load-line-displacement pairs used for the calculation of the unloading compliance (Z9=3). Dependent on the displacement calibration of the system, the number of admissible data pairs should be in excess of 20 (see [29] for a discussion of unloading compliance instrumentation). Some computer-interactive test methods use more than 60 data pairs and to obtain such a large number of points both those from the unloading and the re-loading are used [30]. At the present time it is not possible to determine the optimum number of data pairs for determination of

the unloading compliance of the specimens; however, to assist in the assessment of the over-all acceptability* of data, the linear regression calculations within JRERUN.BAS also give the coefficient of determination, r^2 , for each estimate of unloading compliance. Ideally, this value should be in excess of 0.9999,[22], however, for the B1-B11 series undertaken in this work most of the linear regression calculations for each unloading give values in excess of 0.999. A typical output from JRERUN.BAS is given in Appendix 5, where it can be seen that the coefficients of determination for unloading compliance data are in excess of 0.999. If an increase in the number of data pairs for the unload is found to be desirable then, in the cases of specimen geometries for which the present J-integral test control program has been developed, this can be achieved simply by changing the span control of the MTS-810 system so that the number of bits from the MSG results in a smaller increment in stroke.

Another potential source of error in the single-specimen J-integral test method is in the non-linear unloading effects which occur with some materials. This can introduce significant errors in the calculation of unloading compliance [29] and also small errors in the estimation of area under the load/load-line-displacement curve. To allow for these non-linear effects (time-dependent recovery) a "hold" in the displacement is often desirable before unloading see [22 and 29]. The material tested in this preliminary work was a high strength steel and as a result the non-linear effects at the start of an unload are small. This can be seen in Figure 16, where several unloads are re-plotted by GRAPH [24] after running the data through ACCESS1.BAS on the VAX 11/780. It is noted that a very small degree of non-linearity is evident at the top (start) of the unloading record. To overcome the possibility that any data pairs which may constitute the non-linear part of the record are admitted to the regression analysis the control program (JCTS for example) now discards the first 4 load/load-line-displacement data pairs. In the case of the data analysis programs, JRERUN.BAS on the VAX 11/780 and the PDP 11/04, all data pairs are listed prior to linear regression analysis, and the data can be re-examined and the number to be discarded input before the calculations begin. The number of data pairs which are discarded can vary for successive unloads in the JRERUN.BAS program and hence is listed in the summary of the calculations produced by the program.

Errors in the estimations of A_a , and to a lesser extent the calculation of J, can also arise as a result of electrical and mechanical hysteresis in the load and displacement measurement systems. Using a 250 kN load cell, the load can be measured to within $\pm 1.0\%$ and the displacement clip gauge has a maximum error of $\pm 0.1\%$. Electrical noise is minimised because each load/load-line-displacement data pair is an average of 10 readings taken over 0.01 second.

Looking back to the data in Tables 3(a and b), generated by

* The acceptability of the data can be tested quantitatively on the basis of the accuracy of predicted versus measured a_0 and a_f values.

JRERUN.BAS, it can be seen that the agreement between measured and calculated crack length values is closer than those obtained using the PAFEC-generated compliance calibration for the MRL J03 specimens. The sensitivity of the calculated results to the compliance calibration and Young's modulus value used for the normalization of raw compliance data has been demonstrated in Section 8, and is clearly an important aspect of the appraisal of the test procedure.

It is difficult to assess the accuracies to which the J_{IC} value and corresponding Δa value are measured. All aspects of the calculations and error analyses must be documented during a test or in the re-run of the raw data through JRERUN.BAS.

The final point to be discussed is the accuracy to which the J_{IC} value can be determined from a set of admissible J- Δa data pairs. It is usual to fit a straight line through all admissible data pairs whereby J_{IC} is calculated at the point of intersection of this linear regression line and the blunting line [2]. This method has been used in the present work. However, it is instructive to re-examine some of the results given in Table 4 in more detail. The J_{IC} values under consideration are those obtained from JRERUN.BAS using the experimentally-determined unloading compliance calibration. The calculations for the J_{IC} values are summarized in Table 6.

From the $\pm 95\%$ confidence limits on the estimation of J_{IC} for each of the specimens tested in this work it can be seen that some of the J_{IC} values are poor estimates of fracture toughness. Appreciable errors in the estimation of J_{IC} arise when

- (i) the number of admissible J- Δa data pairs is low.
- (ii) the J- Δa data pairs are grouped away from the 0.15 mm exclusion line and towards the 1.50 mm exclusion line, [2].
- (iii) the J- Δa data pairs exhibit scatter within a single specimen test.

It is clear that the ideal grouping of the J- Δa data points for the purposes of the linear regression analysis is equi-spaced between the exclusion lines and that the number of data pairs should be in excess of 12. This is not satisfied by some of the tests conducted in this work. Where the above criteria are met, as in the cases of specimens B1 and B2, the $\pm 95\%$ confidence interval is small. The data for specimen B4 have been analysed by successively using more J- Δa data in the regression analysis. Unfortunately, where 6 and 9 data points are used the extra data points are to the left of the 0.15 mm exclusion line. However the result demonstrates the need for sufficient data points of optimum spacing. Whether or not the scatter of J- Δa points can be reduced for a single specimen J-integral test is difficult to assess. If all physical aspects of the J-integral test are correct (see above) then any scatter observed in the test data must be regarded as a result of the response of the material to the loading (and unloading) of the J-integral test procedure. The effects of scatter on the estimation of J_{IC} can be reduced by keeping the number of admissible data pairs high and this can be done quite simply using computer-interactive test methods.

TABLE 6

Summary of Linear Regression Calculations for J_{IC} Determinations

Specimen No.	J_{IC} value ⁽¹⁾ $kN\ m^{-1}$	No. of Admissible Data Points	Y Intercept $kN\ m^{-1}$	\pm 95% Confidence ⁽²⁾ limits $kN\ m^{-1}$
B1	72.8	13	70.2	\pm 5.5
B2	78.4	9	73.0	\pm 9.1
B3	80.1	11	71.0	\pm 22.7
B4	not calculated	5	41.9	\pm 75.3
B4	83.8	6	79.5	\pm 32.2
B4	not calculated	9	48.8	\pm 8.8
B6	75.9	7	72.6	\pm 6.8
B8	71.3	no values	-	-
B9	> 60	no values	-	-
B10	57.4	9	55.4	\pm 22.5
B11	> 70	no values	-	-

(1) On the blunting line

(2) On the Y axis

In summary it can be seen that most of the errors discussed above are approximately the same for each test using the MRL J03 specimen. The calculated error in the area under the elastic portion of the load/load-line-displacement curve is consistently $< +2\%$ (but never negative), a_0 and a_f are usually estimated to within $\pm 2\%$ (but if similar unloading compliance calibrations are used the test-to-test variations in crack-length estimates are even smaller) and Δa is usually estimated to within $\pm 15\%$. Thus under most circumstances the computer-interactive single specimen J-integral test using MRL J03 specimens satisfy the standard test method for the measurement of J_{IC} .

11. CONCLUSIONS

A computer-interactive, single specimen J-integral test method has been developed for the PDP11/04-MTS 810 system, and tested using the MRL J03 specimen. The material under test was a Ni-Cr-Mo 4.5 inch gun steel.

- (1) The control program on the PDP11/04 has been shown to conduct a single specimen J-integral test which produces K_{Jc} values which agree well with known plane-strain fracture toughness values.
- (2) The inferred increments in crack length, Δa , obtained using the unloading compliance method incorporated in the control program are usually found to agree within +15% of that obtained by direct measurement. Alternative calibrations and slight changes to the Young's modulus value used in the calculations can be used to improve the correspondence between measured and inferred values of crack length.
- (3) The computer-interactive single specimen J-integral test conforms to the requirements of ASTM standard E 813 for the measurement of J_{Ic} .

12. ACKNOWLEDGEMENTS

The authors are indebted to Mr R. Farrara [27] of US Army Armament Research and Development Command, Benet Weapons Laboratory, for valuable discussions which led to the refinement of the control program for the single specimen J-integral test.

We are also indebted to Mr T.V. Rose for his pioneering program development for this work [3].

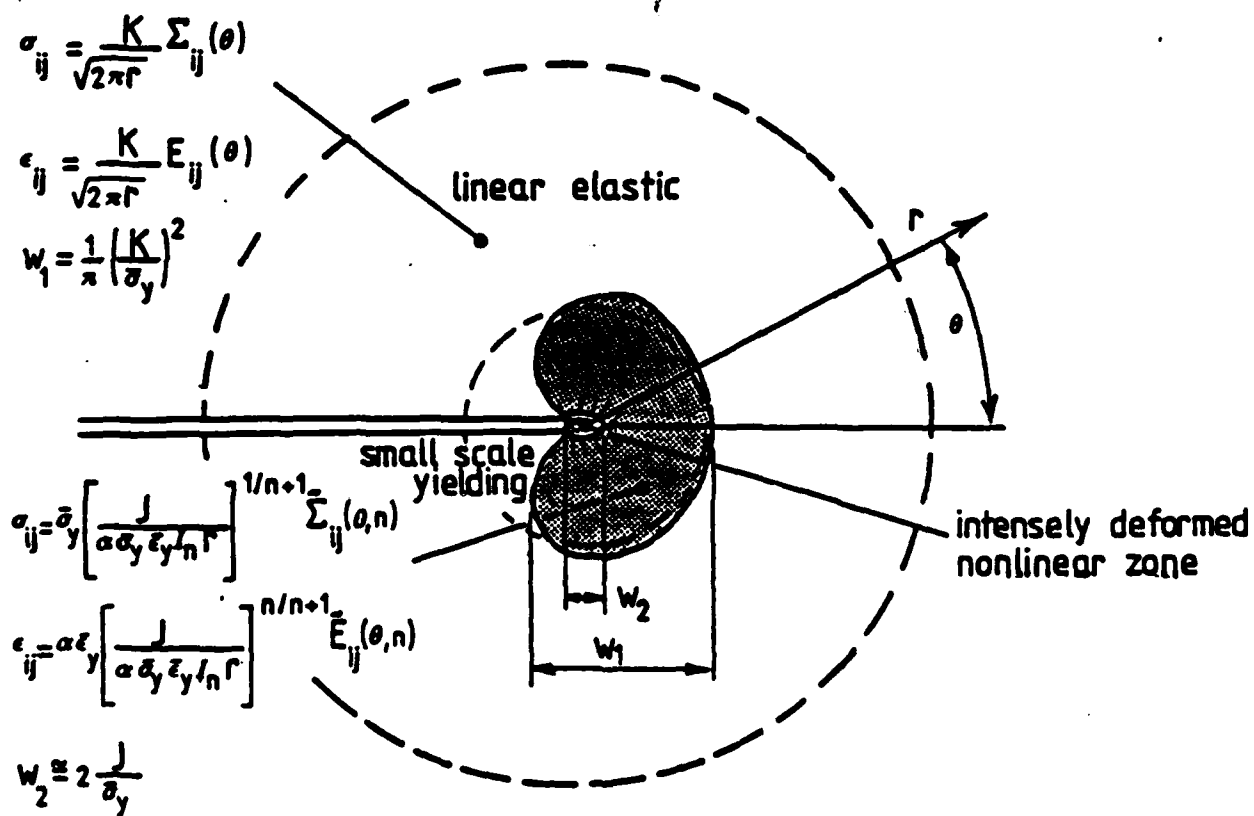


FIGURE 1 Schematic representation of crack-tip stress and strain fields.

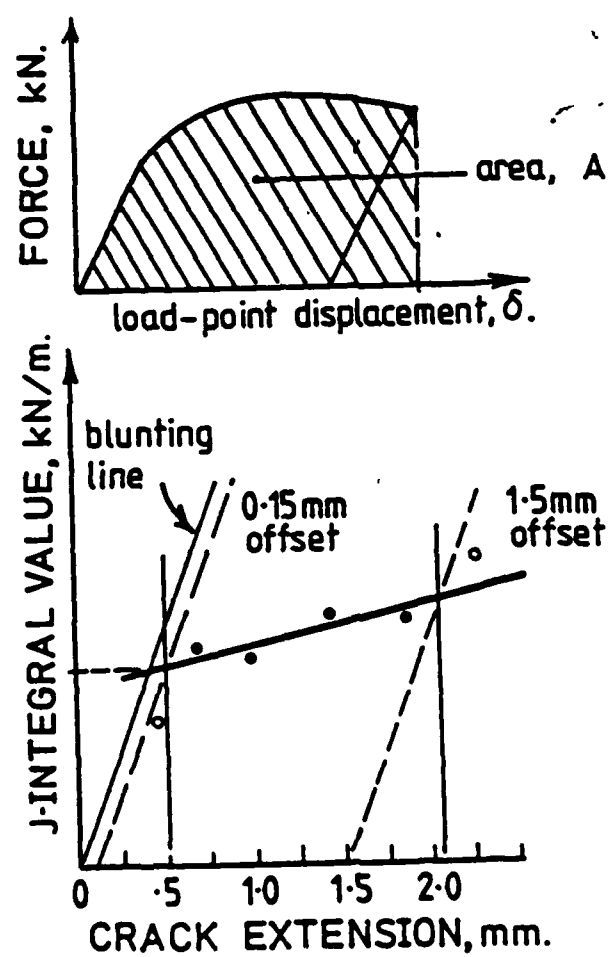


FIGURE 2 ASTM E 813 method for the measurement of J_{IC} .

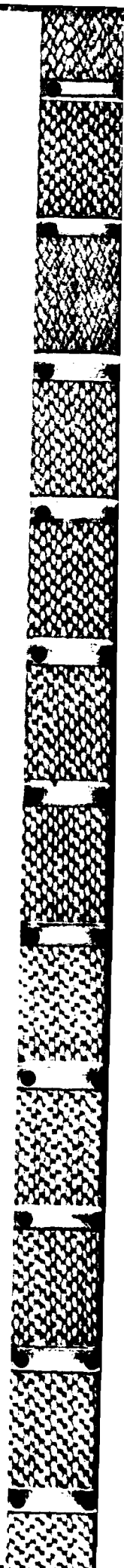


FIGURE 3

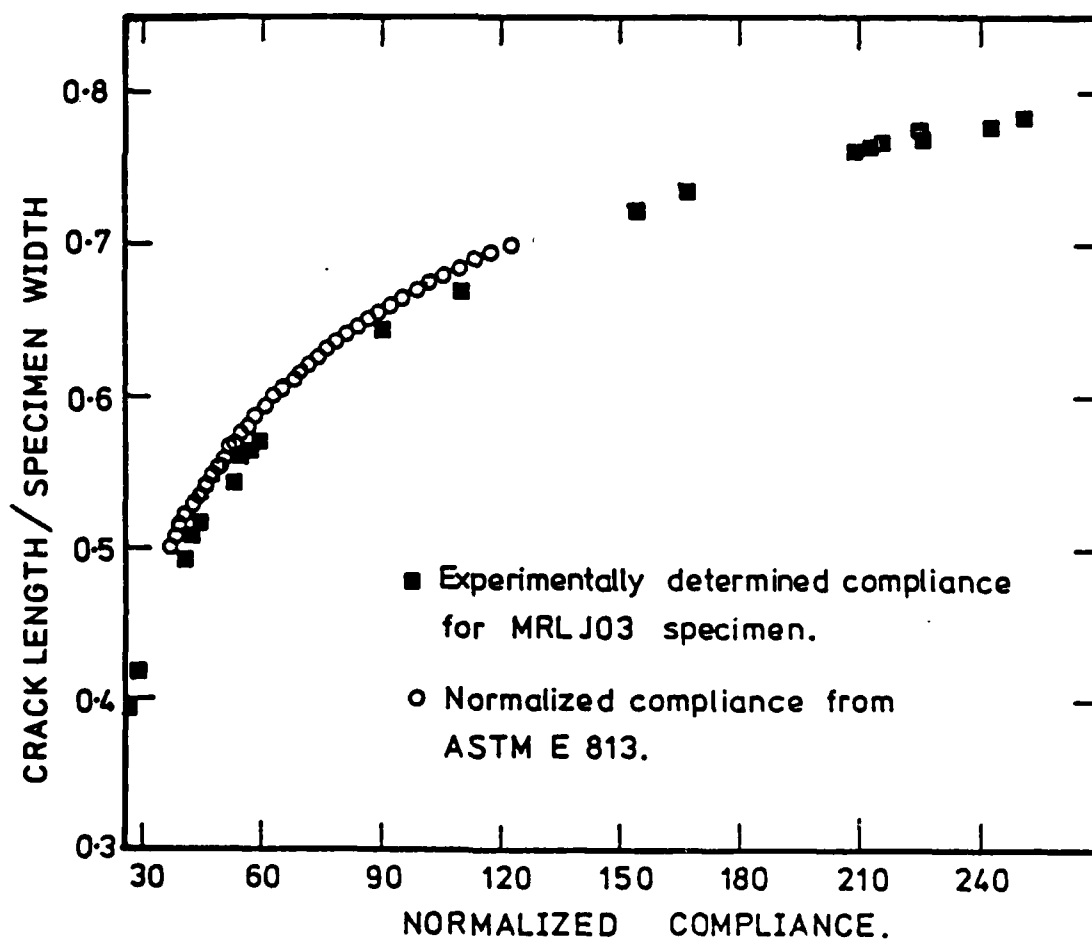


FIGURE 4

An experimental unloading compliance calibration for an MRL J03 specimen, data from [16].

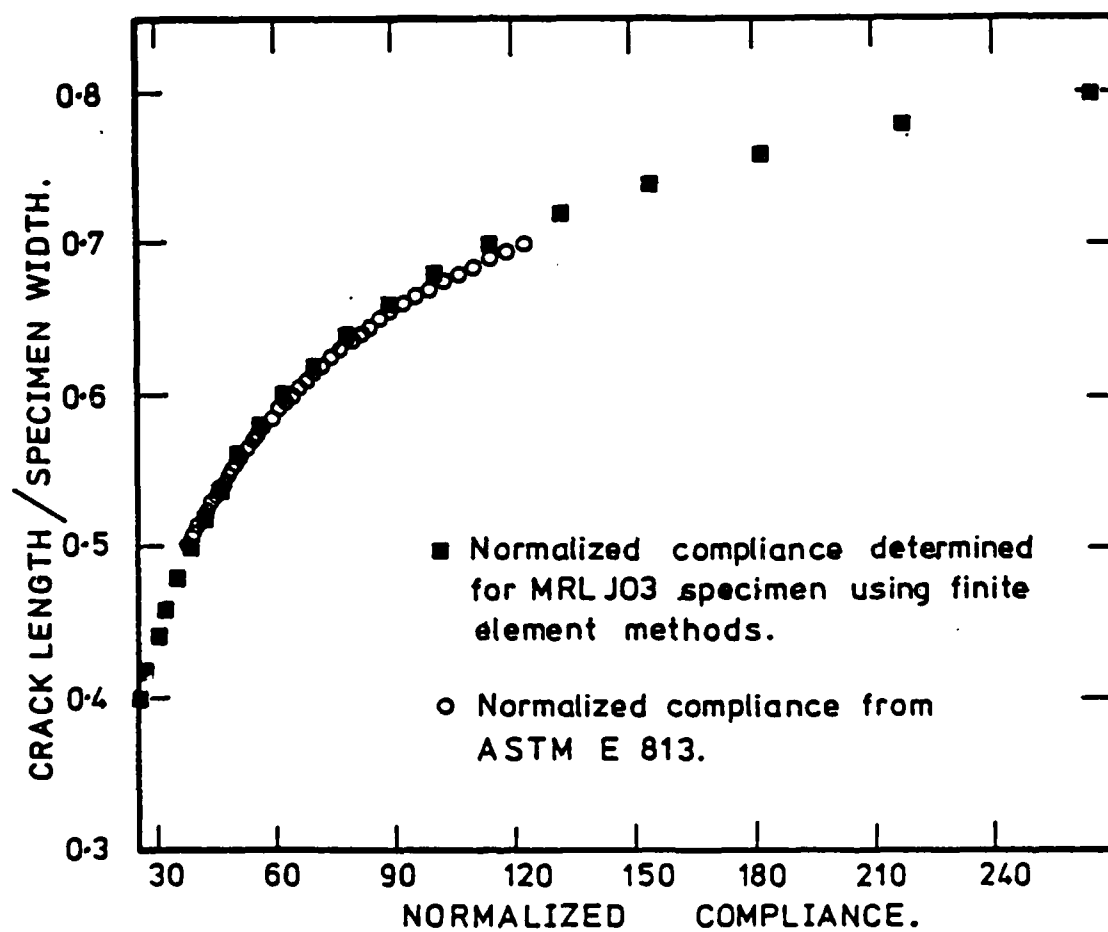


FIGURE 5 An analytical unloading compliance calibration for an MRL J03 specimen, data from [17a].

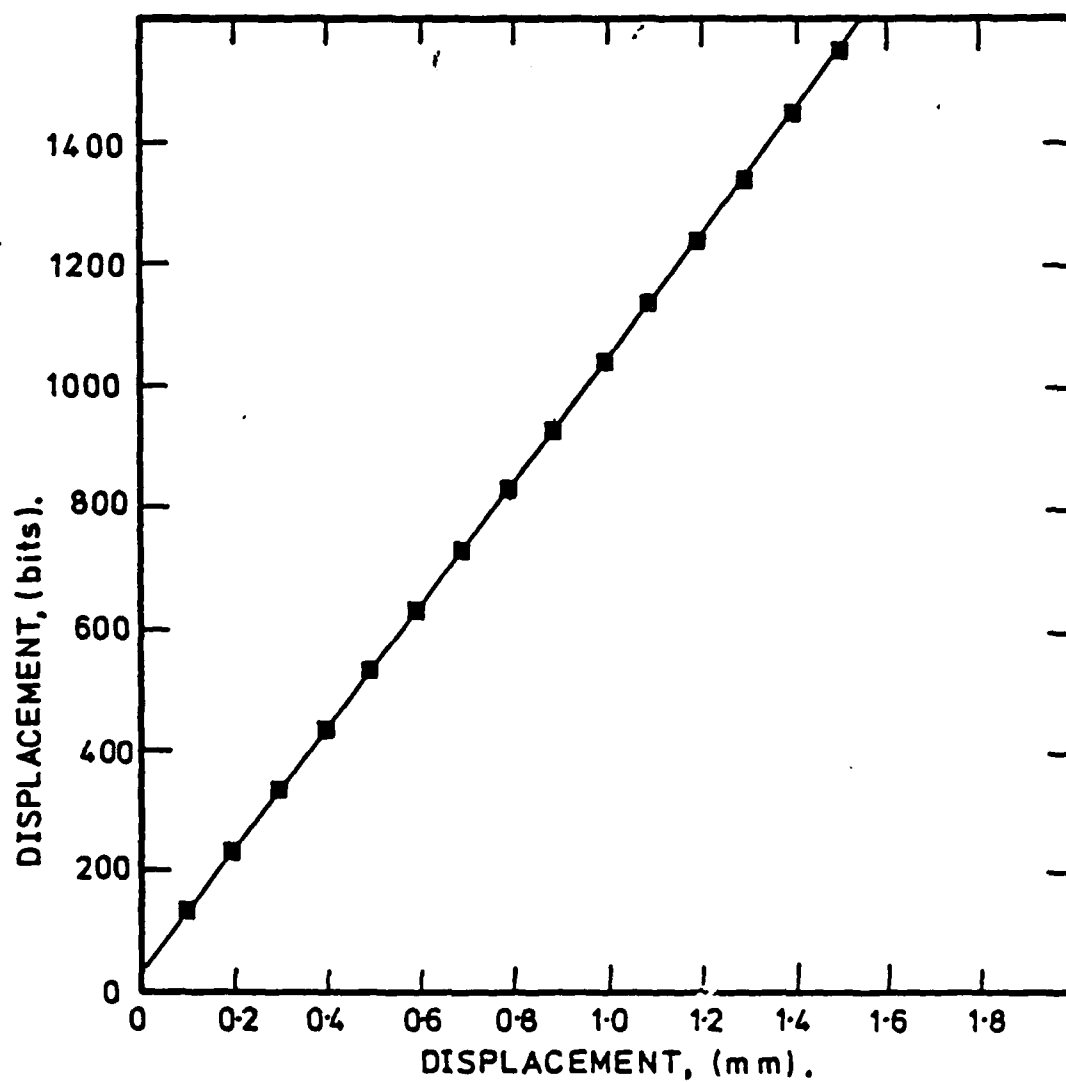


FIGURE 6

The opening and closing voltage output from an MTS 632.02C.20 clip gauge.

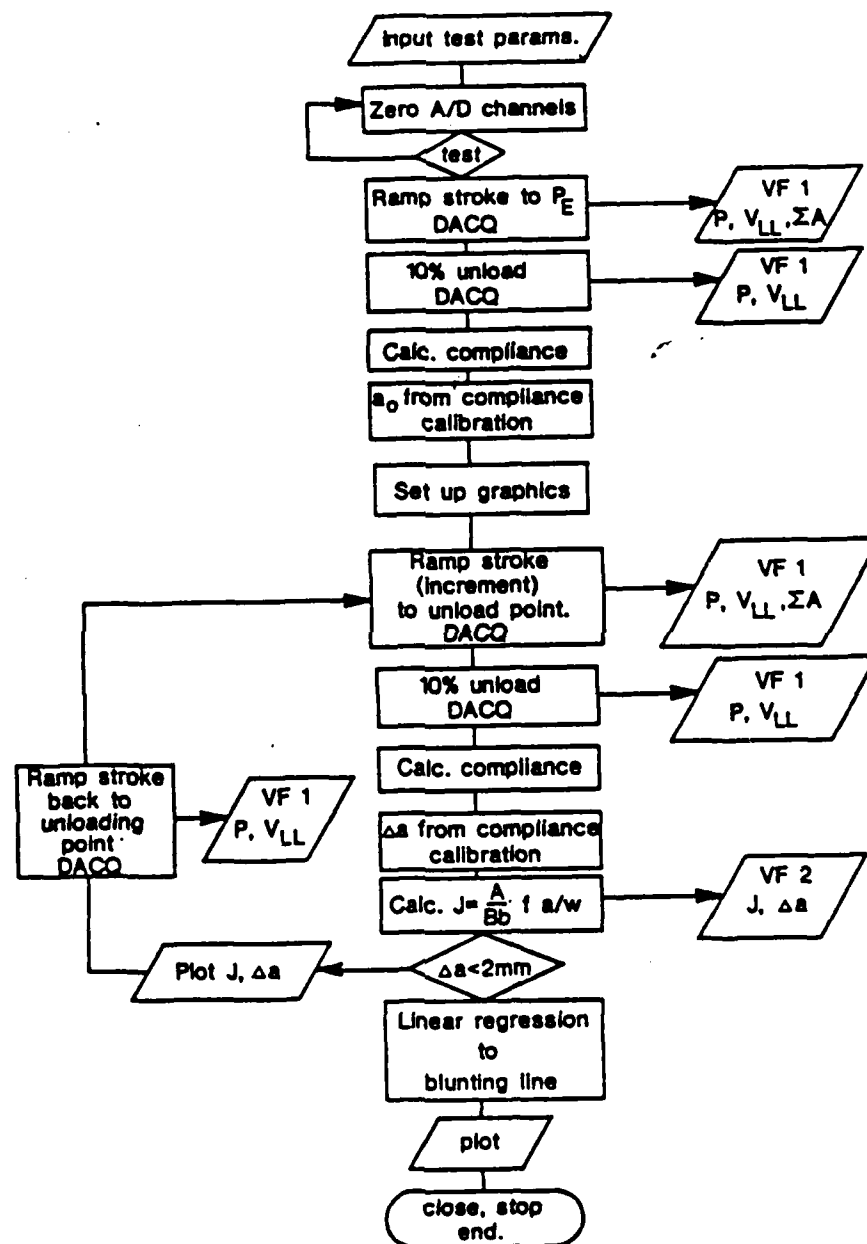


FIGURE 7

Flow diagram for a computer interactive, single specimen J-integral test.

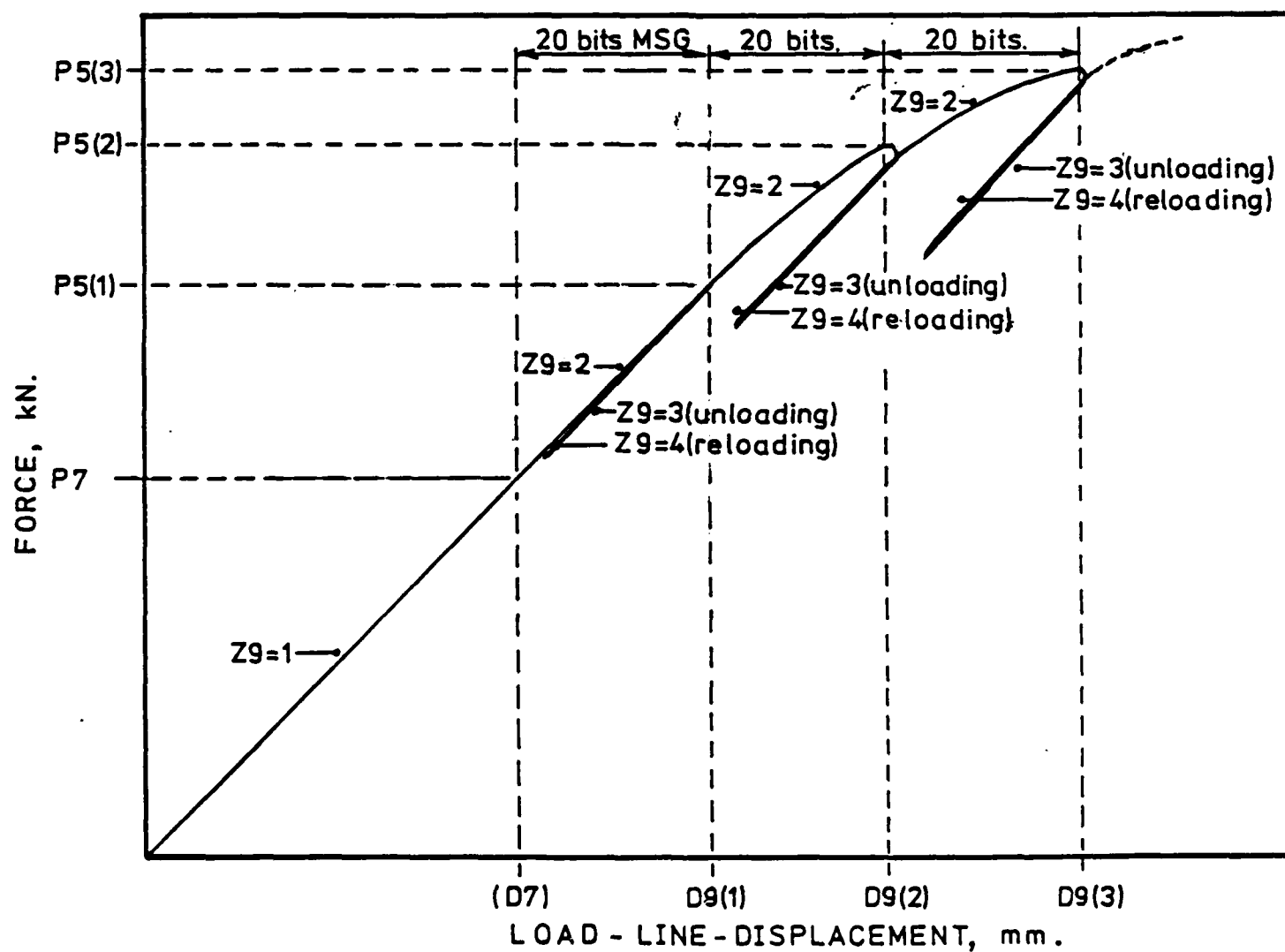


FIGURE 8 Loading, unload and re-load ramps in a single specimen J-integral test.

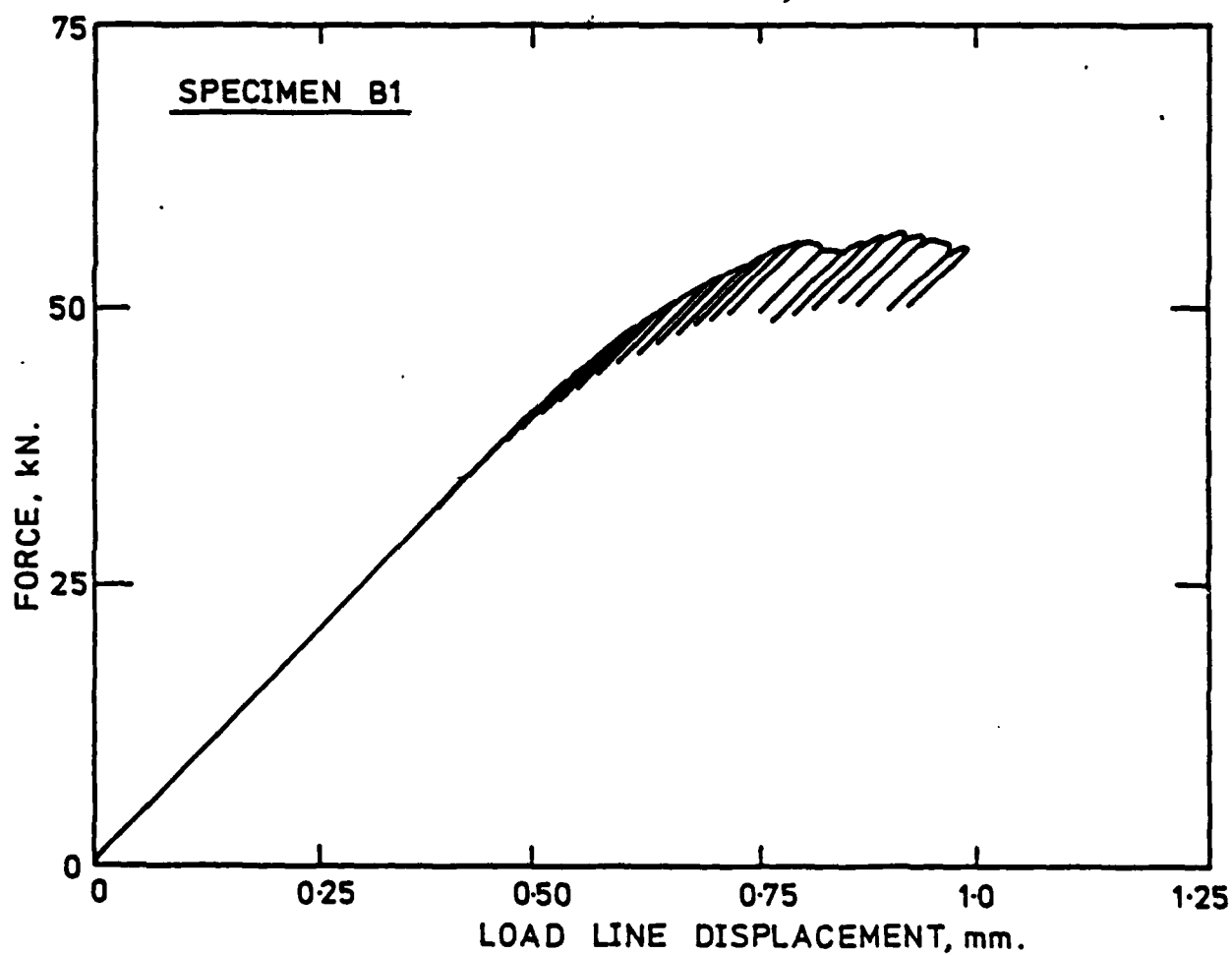


FIGURE 9

A typical force/load-line-displacement analogue output for a single specimen J-integral test.



FIGURE 10 Micrograph of a transverse section through a 4.5 inch Naval gun.
1000X 2% nital etch.

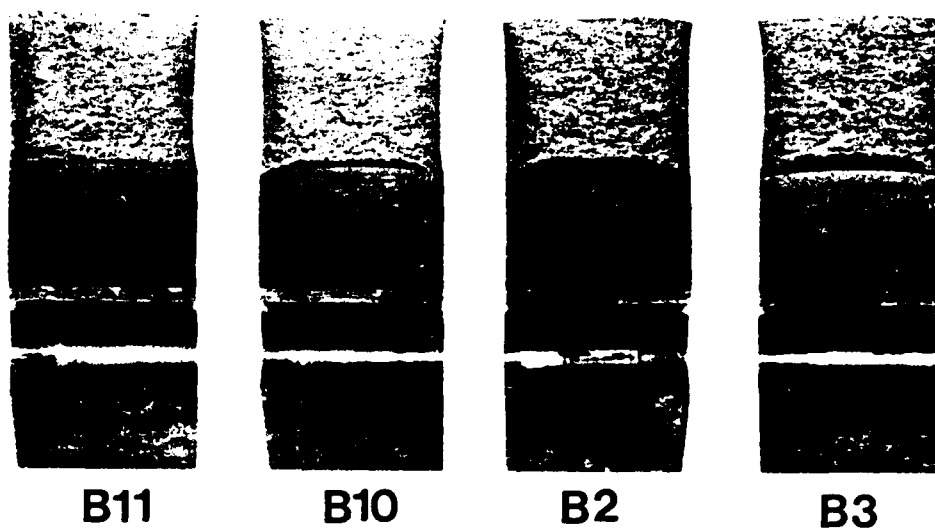


FIGURE 11 Heat tinted specimens to mark final crack lengths in specimens from a 4.5 inch gun barrel of NiCrMo steel.

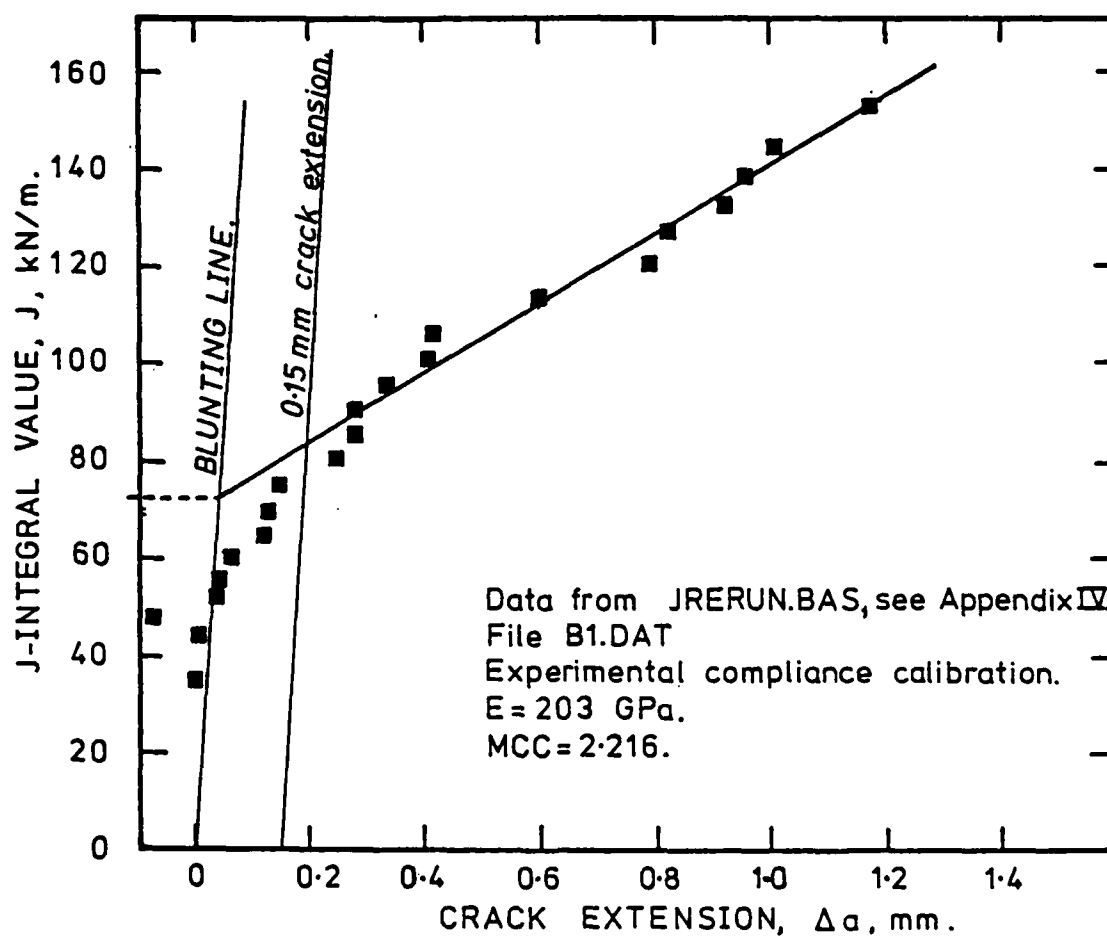


FIGURE 12 A single specimen J - Δa plot for specimen B1.

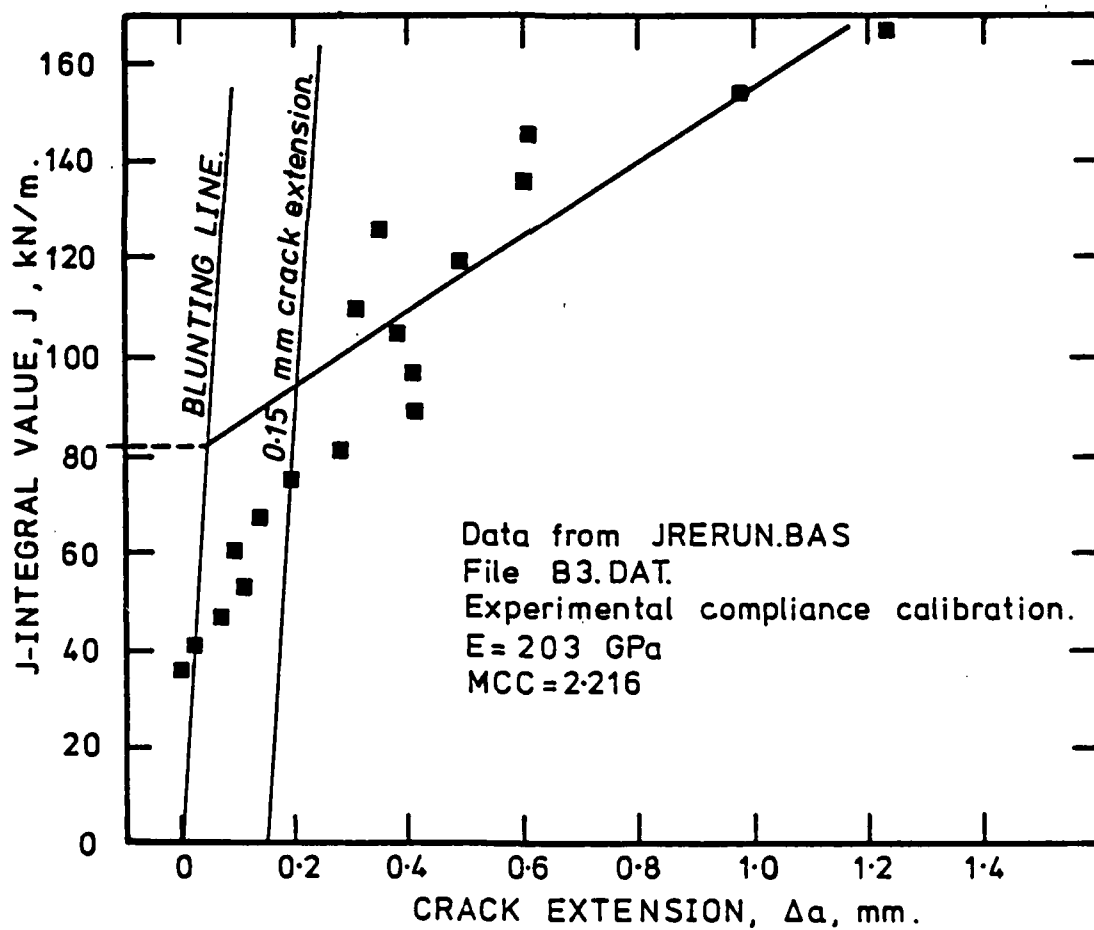


FIGURE 13 A single specimen J- Δa plot for specimen B3.

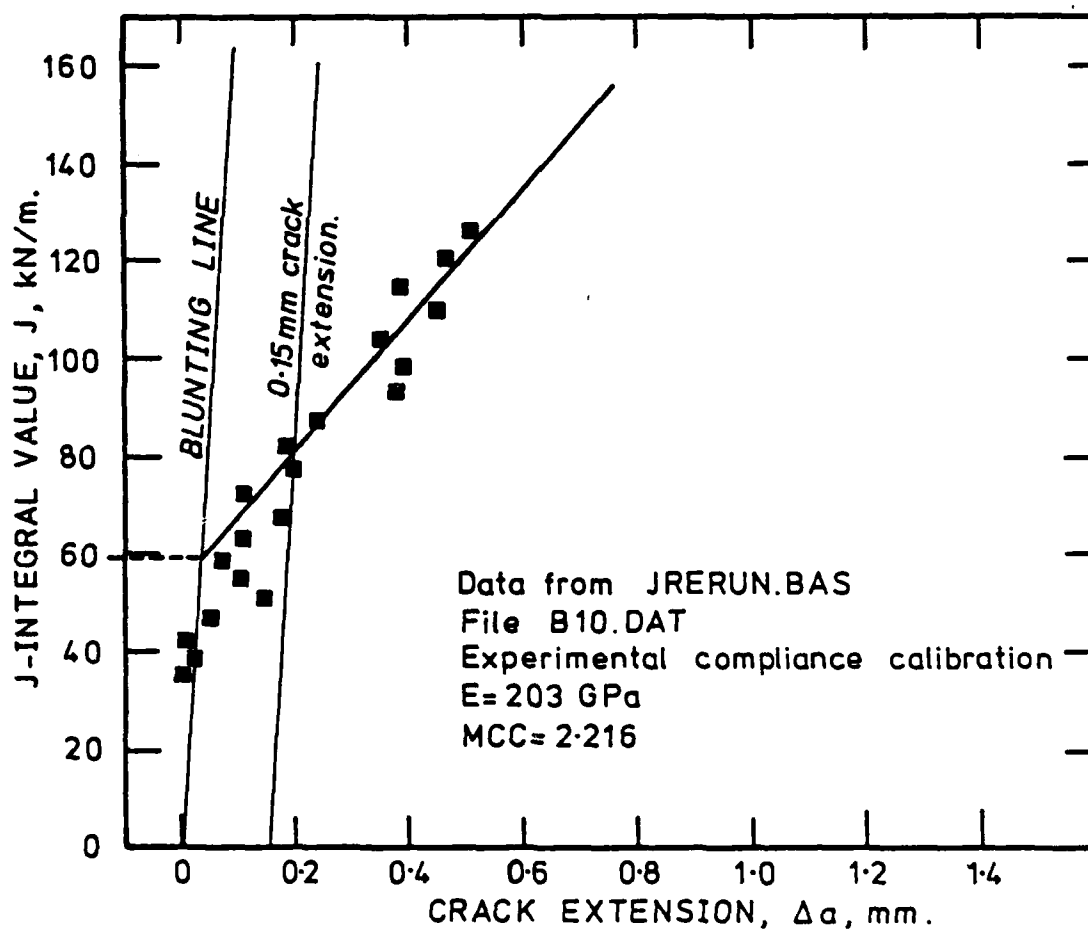


FIGURE 14 A single specimen J- Δa plot for specimen B10.

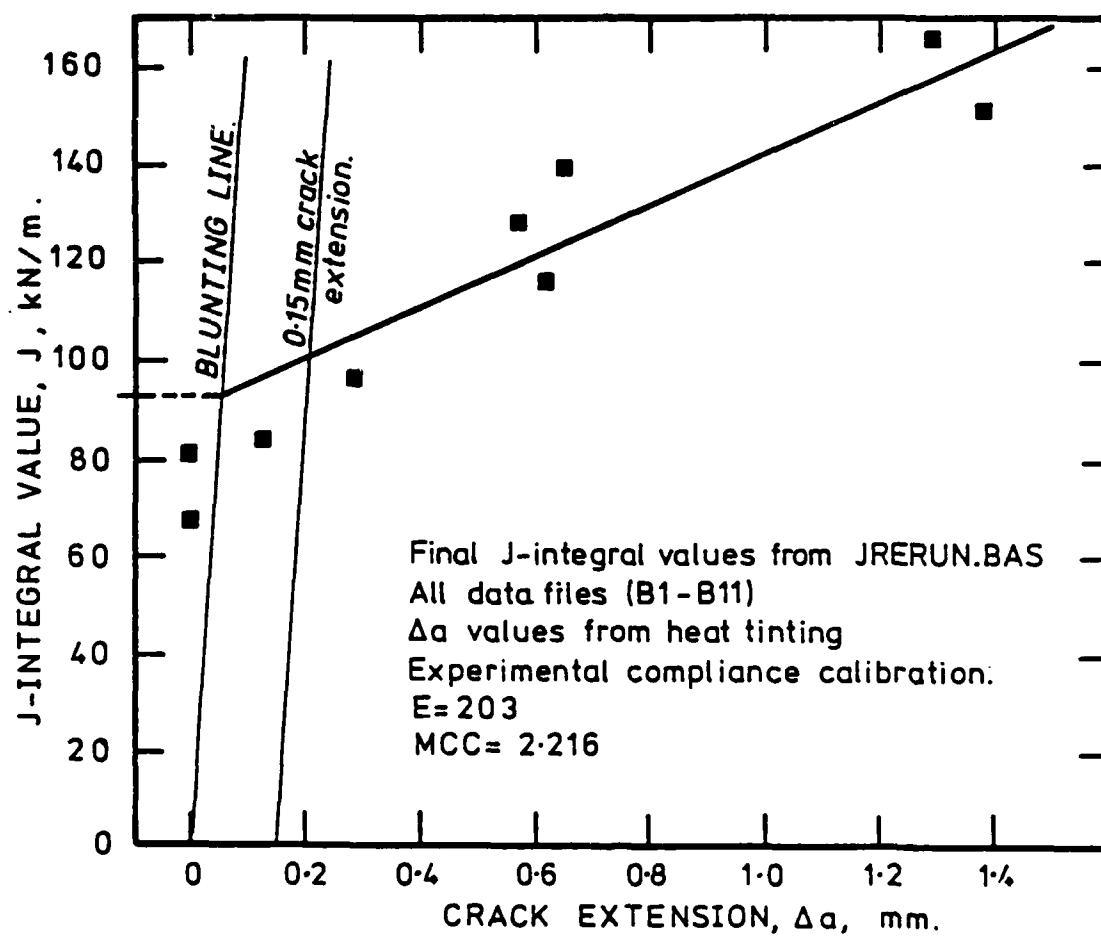


FIGURE 15 The multiple specimen J- Δa plot for all specimens, B1-B11.

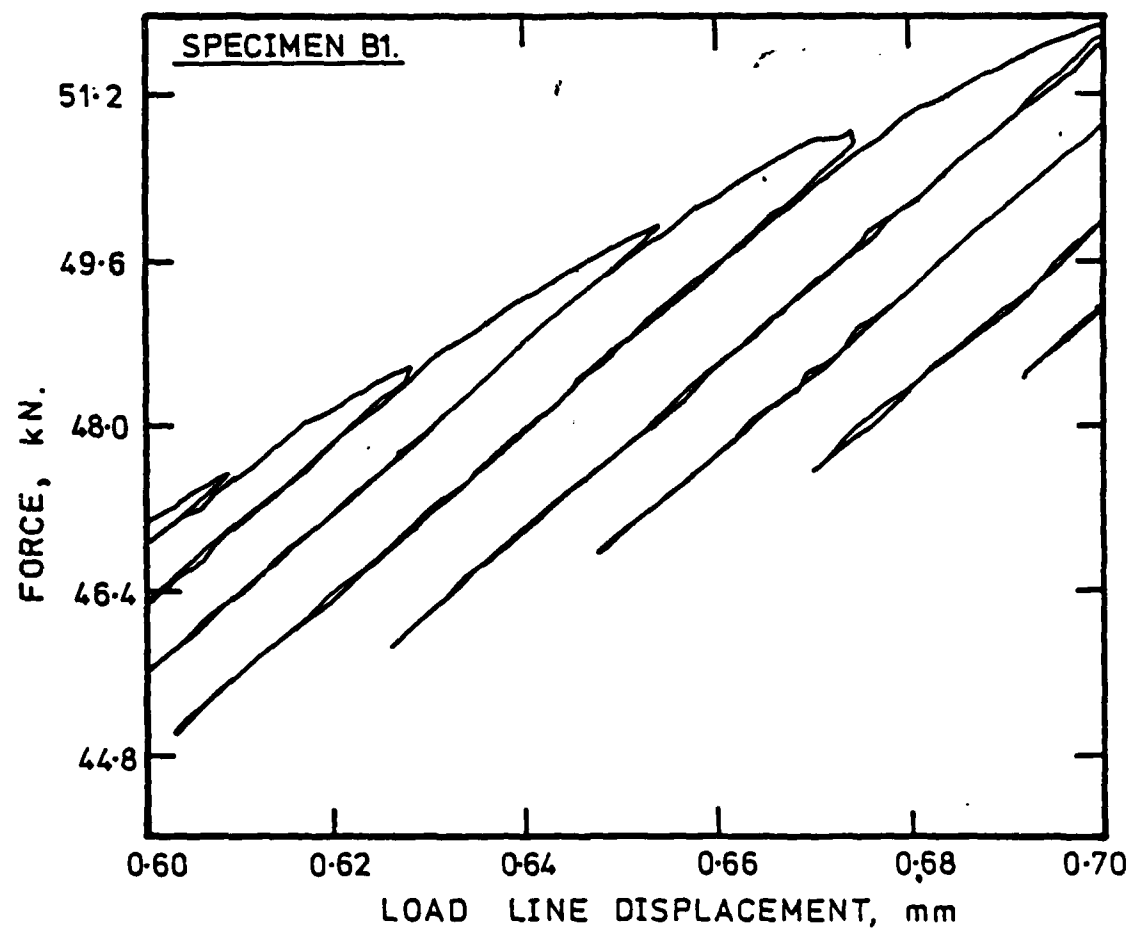


FIGURE 16 An example of the hysteresis in successive unloads and reloads for a NiCrMo gun steel.

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APPENDIX 1

COMPUTER PROGRAM LISTINGS FOR SINGLE SPECIMEN

J INTEGRAL FRACTURE TOUGHNESS TESTS

(a) Program listings for PDP 11/04 Computer.

(1) JCTS.BAS

```
100 REM ...AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGANIZATION
110 REM ...MATERIALS RESEARCH LABORATORIES
120 REM JCTS5.BAS
130 TIME(10)
140 EDUMP / BUTN("S", LINE 2260 )
150 ERASE
160 PRINT
170 PRINT 'THIS PROGRAM CONDUCTS A SINGLE SPECIMEN J TEST'
180 PRINT / PRINT 'THE TEST COMPLIES WITH ASTM 813 '
190 PRINT / PRINT 'NOTE: READ THE QUESTIONS CAREFULLY'
200 PRINT ' FOR A LISTING OF ALL PARAMETERS RUN "JLIST.BAS"'
210 PRINT '<CR> '; / INPUT Z$
220 ERASE / PRINT '***** MTS ANALOG SET UP ROUTINE ***** / PRINT
230 PRINT 'ENSURE:-'
240 PRINT '- STRAIN CHANNEL IS CONNECTED TO COMPUTER'
250 PRINT '- STROKE CTRL ***** RANGE MUST BE +-10 MM *****
260 PRINT '- SPECIMEN OUT'
270 N7=N7+1
280 PRINT '- HYDRAULICS ON'
290 PRINT '- PROGRAM CTRL IS LOCAL'
300 PRINT / PRINT 'MASTER CLEAR (CHNL 4 MUST = 000),<CR>';
310 INPUT Z$ / PRINT
320 PRINT 'SET PROGRAM CTRL TO REMOTE, <CR> ';
330 INPUT Z$ / PRINT
340 PRINT 'ADJUST SET POINT TO GIVE ZERO DISP (CHNL3=000)'
350 PRINT '***** WARNING *****'
360 PRINT ' RAM WILL MOVE SO ENSURE CLEARANCE WITH STROKE ZERO'
370 PRINT '<CR> '; / INPUT Z$ / PRINT
380 PRINT ' INSERT SPECIMEN USING STROKE ZERO, <CR> ';
390 INPUT Z$ / PRINT
400 PRINT 'SPAN #1 TO 1000,<CR> '; / INPUT Z$ / PRINT
410 PRINT 'INSTALL CLIP GAUGE (632.02C.20) AND ZERO OUTPUT'
420 PRINT 'COARSE ZERO IS ON THE INPUT BOX AND FINE ZERO IS ON THE AMPLIFIER UNIT'
430 PRINT '<CR> '; / INPUT Z$ / PRINT
440 PRINT 'SET UP X-Y RECORDER FOR LOAD / DISP RECORD'
450 PRINT 'USING CALIBRATED 10V POT ON 442 CONTROLLER'
460 PRINT 'IMM = 25 CM (HORIZ) = 5.0 V'
470 PRINT '<CR> WHEN SET UP' / INPUT Z$
480 ERASE / PRINT '***** RANGE SELECTION ***** / PRINT
490 PRINT 'LOAD RANGE (KN)'; / INPUT R0
500 R0=2047/R0 / REM R0 NOW = BITS/KN
510 PRINT 'ENSURE 75% STRAIN RANGE IS SELECTED,<CR> ';
```

```

520 INPUT Z$
530 R1=1011 / REM 1011 BITS IS 1.0MM ON THE 75% STRAIN RANGE
540 F1=80 / REM RAMP RATE=80
550 QUIT
560 ENABL
570 ERASE / PRINT 'TO STOP TEST <BREAK> "S" WILL DUMP THRU LINE15460'
580 PRINT '<CR> TO CONTINUE' / INPUT Z$
590 ERASE / PRINT '***** D/A ZERO READINGS *****' / PRINT
600 P0=0 / D0=0
610 GOSUB 1760 / REM DACQ
620 PRINT 'AVE LOAD = ';P0/(10*R0);' KN (OR ';P0/10;' BITS)'
630 PRINT 'AVE LPD = ';D0/(10*R1);' MM (OR ';D0/10;' BITS)'
640 PRINT 'ZERO RESPECTIVE AMPLIFIER. REPEAT READINGS (Y/N)';
650 INPUT Z$ / IF Z$='Y' THEN 600
660 ERASE / PRINT '***** DATA STORAGE *****' / PRINT
670 PRINT / PRINT 'ENSURE DISK IS IN DY1:'
680 PRINT 'SPECIMEN TITLE'; / INPUT T$
690 OPEN 'DY1:'+T$+'.DAT' FOR OUTPUT AS FILE VF1(20000)
700 FOR Z=0 TO 20000 / VF1(Z)=0 / NEXT Z
710 OPEN 'DY1:'+T$+'.PLT' FOR OUTPUT AS FILE VF2(300)
720 FOR Z=0 TO 300 / VF2(Z)=0 / NEXT Z
730 OPEN 'LS:' FOR OUTPUT AS FILE #1
740 ERASE / PRINT '***** ';T$;' DIMENSIONS *****' / PRINT
750 PRINT 'SPEC WIDTH (METRES) -'; / INPUT W
760 PRINT 'SPEC THICKNESS (METRES) -'; / INPUT B
770 PRINT 'E (GPA) - '; / INPUT M
780 PRINT 'PROOF STRESS (MPA) - '; / INPUT U
790 PRINT 'MERKLE-CORTEN CO-EFFIC. ': / INPUT Q
800 M=M*1.00000E+09 / REM IN N/M 2
810 PRINT / PRINT 'TO RETRIEVE ';T$;' J DATA,RUN <ACCESS>'
820 COPY
830 VF1(0)=B / VF1(1)=W / VF1(2)=M / VF1(3)=R0 / VF1(4)=R1
840 PRINT 'ELASTIC LIMIT (KN)'; / INPUT P7
850 PRINT 'MAX. # OF UNLOADS'; / INPUT U7
860 PRINT '# OF BITS STROKE INCR' / INPUT M7
870 VF2(1)=P7
880 P7=INT(P7*R0)
890 N=0 / N1=0 / Z9=1 / Z=0 / D2=0 / N7=0
900 ERASE / PRINT '** RAMP TO ';P7/R0;' KN THEN J TEST'
910 PRINT / PRINT 'X-Y READY, <CR> TO START TEST'; / INPUT Z$
920 REM PRINT OF DATA FILE
930 PRINT #1,TAB(10)'PLOTING DATA FOR THE 10% UNLOAD J INTEGRAL TEST FOR SPECIMEN ';T$
940 PRINT #1,TAB(5)'READING #';TAB(20)'AREA';TAB(35)'A/W';TAB(50)'DELTA
CRKLENGTH';TAB(75)'J';TAB(85)'E5';TAB(100)'V'
950 PRINT #1,TAB(21)'KNM';TAB(54)'METRES';TAB(72)'KN/M'
960 REM SET UP GRAPHICS
970 ERASE / GRON
980 PHYL(100,975,55,750)
990 SCALE(0,0,2.00000E-03,0,350)
1000 AXES(0,0) / AXES(2.00000E-03,350)
1010 LABEL(T$+' DELTA A, METRES.', ' J VALUE,KN/M',5.00000E-04,25,0)
1020 INVEC / PLOT(0,0) / PLOT(200/(2*U*1000),250) / INVEC
1030 INVEC / PLOT(1.50000E-03,0) / PLOT((200/(2*U*1000))+1.50000E-03,250) / INVEC
1040 GOSUB 1130 / REM RAMP ROUTINE
1050 IF Z9=3 THEN GO TO 1040
1060 IF Z9=5 THEN GO TO 1040

```



```

1070 GOSUB 1870 / REM FIT ROUTINE
1080 MARK(" ",VF2(5*N1+3),J)
1090 PRINT
#1,TAB(7);VF2(5*N1);TAB(22);VF2(5*N1+1);TAB(37);VF2(5*N1+2);TAB(52);VF2(5*N1+3);TAB(70);VF2(5*N1+
4);TAB(85);E5;TAB(100);V
1100 IF VF2(5*N1+3)>-1.80000E-03 THEN 2260 / REM OUT OF PROG
1110 IF N7>-U7 GO TO 2260
1120 GO TO 1040
1130 REM ** RAMP SUB-ROUTINE **
1140 IF Z9=5 THEN Z9=2
1150 DIM S(3)
1160 ON Z9 GO TO 1180,1340,1500,1630
1170 REM
1180 REM RAMP STROKE UP ON LOAD WATCH (Z9=1)
1190 S9=30 / REM S0 IS PRESENT STROKE POSITN
1200 P0=0 / D0=0
1210 S=2 / S(0)=0 S(1)=F1 / S(2)=S9
1220 FG(1,S,1,7,4)
1230 FOR Z=0 TO 1000 / NEXT Z / REM WAIT
1240 N=N+1
1250 GOSUB 1760 / REM DACQ
1260 VF1(5*N)=N / VF1(5*N+1)=P5 / VF1(5*N+2)=D5 / VF1(5*N+4)=Z9
1270 IF N=1 THEN VF1(5*N+3)=P5 / GO TO 1300
1280 P8=((P5+P4)/2)
1290 VF1(5*N+3)=VF1(5*N+2)+(P8)*((D5)-D7)
1300 D7=D5 / P4=P5
1310 IF P5>-P7 THEN 1740
1320 S9=S9+1 / GO TO 1200
1330 REM
1340 REM RAMP STROKE UP ON DELTA DISPL. WATCH (Z9=2)
1350 D9=D5+M7 / REM D9=DISPLACEMENT END LEVEL
1360 P0=0 / D0=0
1370 S=2 / S(0)=0 / S(1)=F1 / S(2)=S9
1380 FG(1,S,1,7,4)
1390 FOR Z=0 TO 1000 / NEXT Z / REM WAIT
1400 N=N+1
1410 GOSUB 1760 / REM TO DACQ
1420 P8=((P5+P4)/2)
1430 VF1(5*N)=N / VF1(5*N+1)=P5 / VF1(5*N+2)=D5 / VF1(5*N+3)=VF1(5*N+2)+(P8)*((D5)-D7)
VF1(5*N+4)=Z9
1440 A3=VF1(5*N+3)
1450 D7=D5 / P4=P5
1460 N5=N / REM LAST READING NUMBER AT LOAD UP
1470 IF D5>-D9 THEN 1740 / REM D9=NEW DISP LIMIT
1480 S9=S9+1 / GO TO 1360
1490 REM
1500 REM RAMP DOWN ON LOAD WATCH (Z9=3)
1510 N7=N7+1
1520 P9=-.9*(P5) / D9=D5 / REM D9 IS DISP AT START OF UNLOAD
1530 P0=0 / D0=0
1540 S=2 / S(0)=0 / S(1)=F1 / S(2)=S9
1550 FG(1,S,1,7,4)
1560 FOR Z=0 TO 1000 / NEXT Z / REM WAIT
1570 N=N+1
1580 GOSUB 1760 / REM DACQ
1590 VF1(5*N)=N / VF1(5*N+1)=P5 / VF1(5*N+2)=D5 / VF1(5*N+3)=A3 / VF1(5*N+4)=Z9

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1600 IF P5<P9 THEN 1740
1610 S9-S9-1 / GO TO 1530
1620 REM
1630 REM RAMP UP TO PRIOR LEVEL ON DISP WATCH (Z9-4)
1640 P0=0 / D0=0
1650 S=2 / S(0)=0 / S(1)=F1 / S(2)=S9
1660 FG(1,S,1,7,4)
1670 FOR Z=0 TO 1000 / NEXT Z / REM WAIT
1680 N=N+1
1690 GOSUB 1760 / REM DACQ
1700 VF1(5*N)-N / VF1(5*N+1)-P5 / VF1(5*N+2)-D5 / VF1(5*N+3)-A3 / VF1(5*N+4)-Z9
1710 IF D5>D9 THEN 1740
1720 S9-S9+1 / GO TO 1640
1730 REM
1740 Z9-Z9+1 / REM RAMP SWITCH
1750 RETURN
1760 REM ** DACQ **
1770 DIM P(10),D(10)
1780 FOR Z=0 TO 10 / P(Z)=0 / D(Z)=0 / NEXT Z
1790 DACQ(3,P,0,10) / DACQ(3,D,1,10)
1800 START
1810 IF P<10 THEN 1810
1820 IF D<10 THEN 1820
1830 QUIT
1840 FOR Z=0 TO 9 / P0=P0+P(Z) / D0=D0+D(Z) / NEXT Z
1850 P5=P0/10 / D5=D0/10
1860 RETURN
1870 REM STRAIGHT LINE FIT
1880 X0=.0748577 / X1=.0178943 / X2=-2.30639E-04
1890 X3=1.50063E-06 / X4=-3.78693E-09
1900 K=R0/(R1*1.00000E+06) / REM SCALING FACTOR FOR VLL/P IN MM/KN
1910 REM SET SUMMATIONS TO ZERO
1920 E1=0 / E2=0 / E3=0 / E4=0 / E5=0 / E6=0 / F=0
1930 IF N1>-1 THEN 2000
1940 REM USING DATA FROM 1ST LOAD
1950 FOR C=INT(.9*N) TO INT(.1*N) STEP -1
1960 E1=E1+VF1(5*C+1) / E2=E2+VF1(5*C+2) / E3=E3+VF1(5*C+1)*VF1(5*C+2)
1970 E4=E4+VF1(5*C+2) 2
1980 F=F+1
1990 NEXT C / GO TO 2060
2000 REM USING DATA FROM 10% UNLOAD
2010 FOR C=(N5+5) TO N STEP +1
2020 E1=E1+VF1(5*C+1) / E2=E2+VF1(5*C+2) / E3=E3+VF1(5*C+1)*VF1(5*C+2)
2030 E4=E4+VF1(5*C+2) 2
2040 F=F+1
2050 NEXT C
2060 REM CALC OF SLOPE
2070 E5=(E3-((E1*E2)/F))/(E4-(E2 2)/F)
2080 V=(K*M*B)/E5 / REM NORM. COMPL.
2090 R=X0+X1*V+X2*V 2+X3*V 3+X4*V 4
2100 Y1=R*W
2110 IF N1>-2 THEN 2210
2120 VF2(3)=Y1
2130 IF N1>-1 THEN 2210
2140 VF2(0)=Y1 / REM ORIGINAL CRACK LENGTH
2150 REM CALC OF Y INTERCEPT

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2160 E6=E1/F-E5*E2/F
2170 REM D8 IS DISPL AFTER ALLOW FOR NONLINEAR EFFECTS
2180 D8=-E6/E5
2190 REM PRELIM ESTIMATE OF AREA (ELASTIC)
2200 VF2(2)=(VF1(5*N+2)-D8)*VF1(5*N+1)/2
2210 N1=N1+1
2220 REM CALC OF J (KN/M)
2230 J=Q*VF1(5*N+3)/(B*(W-Y1)*R0*R1*1000)
2240 VF2(5*N1)-N / VF2(5*N1+1)-VF1(5*N+3)/(R0*R1) / VF2(5*N1+2)-R / VF2(5*N1+3)-Y1-VF2(3)
VF2(5*N1+4)-J
2250 RETURN
2260 DUMP / MSWFG(1,2)
2270 COPY
2280 ERASE / PRINT "END OF TEST .... PROGRAM BY T.V. ROSE AND D.S. SAUNDERS, 1984"
2290 CLOSE / STOP / END

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(2) JRERUN.BAS

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100 REM ...AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND RESEARCH ORGANIZATION
110 REM ...MATERIALS RESEARCH LABORATORIES
120 REM JRERUN... THIS PROGRAM WILL RERUN THE JTEST DATA
130 ERASE
140 PRINT "*****"
150 PRINT "JRERUN, A PROGRAM TO RE-RUN THE J TEST USING THE DATA FILES"
160 PRINT "FROM THE PDP11 ....EDIT LINES 1650-1740 TO CHANGE"
170 PRINT "THE COMPLIANCE CALIBRATION FOR THE MEASUREMENT OF CRACK"
180 PRINT "LENGTH FROM THE UNLOADS (Z9=3
    IN THE TEST DATA FILE) "
190 PRINT "*****"
200 PRINT "<CR> TO CONTINUE "      INPUT Z$
210 PRINT "*****"
220 PRINT "SPECIMENS FOR WHICH UNLOADING COMPLIANCE CALS. ARE AVAILABLE"
230 PRINT "SPEC GEOMETRY";TAB(40)"TYPE"
240 PRINT "MRL J03...PAFEC 1984";TAB(40)"1"
250 PRINT "MRL J03...EXPTAL COMP ";TAB(40)"2"
270 PRINT "*****"
*****
280 PRINT "INPUT SPECIMEN TYPE " / INPUT Y
290 ON Y GOSUB 1650,1700
300 PRINT NS
310 PRINT / PRINT
320 PRINT 'WHAT IS THE OUTPUT DATA FILE NAME VIZ NAME ' / INPUT TS
330 OPEN 'DY1:'+TS+'.DAT' FOR INPUT AS FILE VF1(10000)
350 OPEN 'LS:' FOR OUTPUT AS FILE #1
360 PRINT "HOW MANY READINGS IN THE FILE " / INPUT Q
370 PRINT "WHAT IS THE MERKLE CORTEN COEF FOR THIS SPEC. " / INPUT MS
380 DIM P(40),L(40),A(40),
    N(40)
390 DIM R5(40),Q5(40),A5(40),U5(40),J5(40)
400 DIM F5(40),V5(40),C5(40),T5(40)
410 Z9=2 / N7=0
420 PRINT VF1(3);"BITS/KN"
430 PRINT VF1(4);"BITS/MM"
440 PRINT "SPECIMEN DIMENSIONS SHOULD BE MEASURED WITH A MICROMETER"
450 PRINT "SPECIMEN THICKNESS (METRES) " / INPUT B
460 PRINT "SPECIMEN WIDTH (METRES) " / INPUT W
470 ERASE
480 PRINT "YOUNGS MODULUS IS ";VF1(2);"PA"
490 M=VF1(2)
500 PRINT "DO YOU WISH TO CHANGE YOUNGS MODULUS Y/N " / INPUT SS
510 IF SS="N" GO TO 540
520 PRINT "WHAT IS THE NEW VALUE,...IN GPA " / INPUT M
530 M=M*1.00000E+09
540 PRINT / PRINT
550 PRINT "CHECK OF VARIABLES"
560 PRINT "B=";B,"W=";W,"M=";M,"MERKLE-CORTEN COEFF=";MS
570 PRINT "OK? <Y/N>"      INPUT SS
580 IF SS<>"Y" THEN GO TO 440

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590 N3=VF1(3)
600 N4=VF1(4)
610 K=N3/(N4*1.00000E+06)
620 FOR I=2 TO Q+1
630 Z=VF1(5*I-1)
640 IF Z=1 GO TO 680
650 IF Z=2 THEN N=0
660 IF Z=(Z9-1) THEN GOSUB 880
670 IF Z=3 THEN GOSUB 710
680 NEXT I
690 IF Z=3 THEN GO TO 880
700 GO TO 1290
710 REM DATA ACQUISITION
    FROM PDP11 DATA FILE
720 IF N<0 THEN GO TO 760
730 PRINT
740 PRINT "UNLOADING COMPLIANCE DATA" / PRINT
750 PRINT "READING", "LOAD", "DISPL.", "AREA"
760 N6=VF1(5*I-5)
770 P=VF1(5*I-4)
780 L=VF1(5*I-3)
790 A=VF1(5*I-2)
800 P(N)=P
810 L(N)=L
820 A(N)=A
830 N(N)=N6
840 PRINT N(N), P/N3, L/N4, A/(N3*N4)
850 N=N+1
860 Z9=Z / N5=N
870 RETURN
880 PRINT / PRINT / PRINT
890 PRINT "UNLOADING COMPLIANCE RERUN"
900 REM SET SUMMATIONS TO ZERO
910 E1=0 / E2=0 / E3=0 / E4=0 / E5=0 / E6=0
920 E7=0 /
E8=0 / E9=0 / V1=0 / F=0
930 PRINT "MAX. NO OF UNLOADING POINTS IS ";N5
940 PRINT "HOW MANY TO BE DISCARDED " / INPUT O
950 IF (N5=0)<3 THEN PRINT "ERROR...NOT ENOUGH DATA POINTS!" / GO TO 940
960 FOR C=(0+0) TO (N5-1)
970 E1=E1+P(C) / E2=E2+L(C) / E3=E3+P(C)*L(C)
980 E4=E4+L(C) 2 / E6=E6+P(C) 2
990 F=F+1
1000 NEXT C
1010 REM CALC OF SLOPE
1020 E8=E3-((E1*E2)/F) / E9=E4-((E2 2)/F)
1030 E5=E8/E9
1040 REM CALC OF CORR COEFF
1050 V1=E6-((E1 2)/F)
1060 E7=(E8 2)/(E9*V1)
1070 V=(K*M*B)/E5      REM NO
RM COMPLIANCE
1080 V5(N7)=V / C5(N7)=E7
1090 R=X0*X1*V+X2*V 2+X3*V 3+X4*V 4
1100 IF N7>-1 GO TO 1120
1110 Y1=R*W / Y0=Y1 / GO TO 1130

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1120 Y1=R*W
1130 PRINT "CHECK OF UNLOADING POINTS ";F;" SHOULD BE ";N5-O
1140 PRINT "CRACKLENGTH -";Y1;"METRES"
1150 PRINT "READING", "DATA POINTS", "NORM COMPL", "CORR COEFF", "AREA", "A/W", "DELTA A", "J VALUE
1160 J=M5*A(C)/(B*(W-Y1)*N3*N4*1000)
1170 U=N6-N5+1
1180 PRINT U,F,V,E7,A(C)/(N3*N4),R,Y1-Y0,J
1190 Z9-Z
1200 U5(N7)=U / A5(N7)-A(C)/(N3*N4) / R5(N7)-R
1210 Q5(N7)=Y1-Y0 / J5(N7)-J / F5(N7)-F / T5(N7)-N5
1220 PRINT "<CR> TO CONTINUE TO NEXT UNLOADING SET" / INPUT X5
1230 N7=N7+1
1240 IF I<Q THEN GO TO 1280
1250 PRINT "LAST UNLOADING DATA SET"
1260 PRINT "<CR> TO CONTINUE..PRINT OUT ON LS:" / INPUT X5
1270 GO TO 1290
1280 RETURN
1290 CLOSE VF1
1300 PRINT #1,"*****";T5;"*****";T5;"*****";T5;"*****"
1310 PRINT #1 / PRINT #1
1320 PRINT #1,"SUMMARY OF UNLOADING COMPLIANCE CALCS"/
1330 PRINT #1,"USING PDP11/04 DATA FILES AND RUN ON THE PDP11/04"
1340 PRINT #1,"FOR FILE ";T5
1350 PRINT #1, / PRINT #1,
1360 PRINT #1,"YOUNG'S MODULUS FOR THESE CALCULATIONS -";M;"PA"
1370 PRINT #1,"SPECIMEN THICKNESS -";B;"METRES"
1380 PRINT #1,"SPECIMEN WIDTH -";W;"METRES"
1390 PRINT #1 / PRINT #1
1400 PRINT #1,N5
1410 PRINT #1,"POLYNOMIAL FIT COEFFS"
1420 PRINT #1,"X0-";X0;" X1-";X1;" X2-";X2
1430 PRINT #1,"X3-";X3;" X4-";X4;" X5-";X5
1440 PRINT #1 / PRINT #1
1450 PRINT #1,"MERKLE-CORTEN COEFF- ";M5
1460 PRINT #1 / PRINT #1
1470 PRINT #1,"READING # AT", "TOTAL NO. OF", "DATA POINTS", "NORM COMPL", "CORR
COEFF", "AREA", "A/W", "DELTA A", "J VALUE"
1480 PRINT #1,"TOP OF UNLD",TAB(14),"DATA POINTS";TAB(28),"USED"
1490 FOR N=0 TO N7-1
1500 PRINT #1,U5(N),T5(N),F5(N),V5(N),C5(N),A5(N),R5(N),Q5(N),J5(N)
1510 NEXT N
1520 PRINT #1 / PRINT #1
1640 GO TO 1800
1650 REM
1660 N5='J03 CAL. FROM PAFEC 1984'
1670 X0=.0748577 / X1=.0178943 / X2=-2.30639E-04
1680 X3=1.50063E-06 / X4=-3.78693E-09
1690 RETURN
1700 REM
1710 N5='J03 CAL. FROM CLARK EXPT DATA, 1983 '
1720 X0=.106976 / X1=.0147547 / X2=-1.62423E-04
1730 X3=8.75445E-07 / X4=-1.77957E-09
1740 RETURN
1750 REM
1800 PRINT #1,"END OF JRERUN.BAS... PROGRAM BY D.S.SAUNDERS AND I.A.BURCH....1986"
1805 CLOSE
1810 END

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(3) ACCESS.BAS

```
100 REM ...AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGANIZATION
110 REM ...MATERIALS RESEARCH LABORATORIES
120 REM ACCESS PROGRAM TO ACCESS DATA IN THE *****.DAT FILE AND THE *****.GRA FILE FOR THE 10%
UNLOAD J TEST
130 PRINT 'WHAT IS THE DATA FILE NAME?' INPUT T$
140 OPEN 'DY1: '*T$+'.DAT' FOR INPUT AS FILE VF1(30000)
150 OPEN 'LS:' FOR OUTPUT AS FILE #1
160 OPEN 'DY1: '*T$+'.PLT' FOR INPUT AS FILE VF2(500)
170 PRINT 'TEXT REQUIRED? Y/N' INPUT Z$
180 IF Z$='N' GO TO 270
190 PR
INT
#1,TAB(5);"....."
200 PRINT #1,TAB(5);"*****THE DATA STORED IN THIS PDP/11 VIRTUAL FILE IS IN BINARY
FORMAT*****"
210 PRINT #1,TAB(5);"LOAD THE DISK ON TO THE VAX, THEN RUN V.BAS ON THE VAX, THEN THIS WILL
CREATE"
220 PRINT #1,TAB(5);"AN OUT PUT FILE OF THE ORIGINAL PDP/11 DATA, AND IN THE SAME LISTING
FORMAT."
230 PRINT #1,TAB(5);"USE THIS OUTPUT FILE TO CREATE A PLOTTING DATA FILE TO USE WITH THE GRAPH "
240 PRINT #1,TAB(5);"PLOTTING ROUTINE. THE DATA CAN BE REPLOTTED AND REANALYSED USING THIS
ROUTINE"
250 PRINT #1,TAB(5);"***** THE VAX ROUTINES ARE 1) V.BAS AND 2) ACCESS1.BAS
*****"
260 PRINT #1,TAB(5);".....
....."
270 PRINT #1 / PRINT #1
280 PRINT #1,TAB(20);T$;' TEST DETAILS'
290 PRINT #1,TAB(20)'SPECIMEN THICKNESS ';VF1(0);' M'
300 PRINT #1,TAB(20)'SPECIMEN WIDTH';VF1(1);' M'
310 PRINT #1
320 R0=VF1(3) /
R1=VF1(4)
330 PRINT #1,TAB(20)'SCALING CONSTANTS FOR ';T$;' TEST'
340 PRINT #1,TAB(25)'FOR LOAD, R0= ';R0;' BITS/KN'
350 PRINT #1,TAB(25)'FOR DISPL, R1= ';R1;' BITS/MM'
360 PRINT #1
370 PRINT 'DO YOU REQUIRE A PRINTOUT FROM THE DATA FILE? (Y/N)'
380 INPUT Z$ / IF Z$='N' THEN 740
390 PRINT 'DO YOU WANT TO ACCESS ALL THE DATA Y/N' / INPUT Z$
400 IF Z$='Y' GO TO 440
410 PRINT 'WHAT VALUE DO YOU WANT TO START AT?' / INPUT V
420 PRINT 'WHAT VALUE DO YOU WANT TO FINISH AT?' / INPUT W
430 GO TO 450
440 V=1 / W=2000
450 PRINT 'THE DATA FILE IS STORED IN BITS'
460 PRINT 'DO YOU WANT THE DATA FROM ';T$;' IN KN,MM AND KNM? (Y/N)' / INPUT Y$
470 IF Y$='N' THEN 610
480 IF X$='Y' THEN 345
490 PRINT #1,TAB(18)'TEST DATA FOR THE 10% UNLOAD J INTEGRAL TEST'
500 PRINT #1,TAB(28)'DATA FROM VIRTUAL FILE ';T$;'.DAT'
510 PRINT #1
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520 PRINT #1,TAB(5)'READING #';TAB(23)'LOAD';TAB(37)'DISPL';TAB(50)'UNCORR. AREA';TAB(65)
SWITCH'
530 PRINT #1,TAB(25)'KN';TAB(39)'MM';TAB(56)'KNM'
540 PRINT #1
550 FOR Z=V
TO W
560 IF VF1(5*Z)=0 THEN 590
570 PRINT
#1,TAB(7);VF1(5*Z);TAB(20);VF1(5*Z+1)/R0;TAB(35);VF1(5*Z+2)/R1;TAB(52);VF1(5*Z+3)/(R0*R1)
;VF1(5*Z+4)
580 NEXT Z
590 PRINT #1 / PRINT #1 / PRINT #1
600 GO TO 740
610 REM THIS PART PRINTS OUT DATA FROM THE JTEST.DAT VF
620 PRINT #1,TAB(18)'TEST DATA FOR THE 10% UNLOAD J INTEGRAL TEST'
630 PRINT #1,TAB(32)'DATA FOR ';T5;' TEST'
640 PRINT #1,
650 PRINT #1,TAB(5)'READING #';TAB(20)'LOAD';TAB(35)'DISPL';TAB(50)'UNCORR. AREA';TAB(65)'
SWITCH'
660 PRIN
T #1,TAB(20)'BITS';TAB(36)'BITS';TAB(52)'BITS*BITS'
670 PRINT #1
680 FOR Z=V TO W
690 IF VF1(5*Z)=0 THEN 740
700 PRINT
#1,TAB(7);VF1(5*Z);TAB(22);VF1(5*Z+1);TAB(35);VF1(5*Z+2);TAB(52);VF1(5*Z+3);TAB(67);VF1(5
710 NEXT Z
720 PRINT #1 / PRINT #1 / PRINT #1 / PRINT #1
730 GO TO 840
740 REM THIS PART PRINTS OUT DATA FROM THE JTEST.GRA VF
750 PRINT 'THIS PROGRAM WILL NOW ONLY PRINT OUT DATA FROM THE J CALCULATION FILE (VF2)'
760 PRINT #1,TAB(20)'INITIAL CRACK LENGTH FROM ELASTIC LOADING';VF2(0);'M'
770 PRINT #1,TAB(20)'ELASTIC LOAD LIMIT FOR THE TEST ';VF2(1);'KN'
780 PRINT #1,TAB(20)'CRACK LENGTH CALCULATED FROM THE FIRST UNLOADING';VF2(3);'M'
790 A1=VF2(6) / A2=VF2(2)/(VF1(3)*VF1(4))
800 F9=(A1-A2)*100/A2
810 PRINT #1,TAB(20)'ERROR IN 1ST AREA CALCULATION AT THE ELASTIC LOAD LIMIT'
820 PRINT #1,TAB(20)'IS... A(MEAS)-A(CALC)/A(CALC)...- ';F9;'%'
830 PRINT #1 / PRINT #1
840 PRINT #1,TAB(18)'PLOTING DATA FROM THE 10% UNLOAD J INTEGRAL TEST'
850 PRINT #1,TAB(32)'DATA FOR ';T5;' TEST'
860 PR
INT #1
870 PRINT #1,TAB(5)'READING #';TAB(20)'AREA';TAB(37)'A/W';TAB(53)'DELTA';TAB(72)'J'
880 PRINT #1,TAB(52)'CRACKLENGTH'
890 PRINT #1,TAB(20)'KNM';TAB(53)'METRES';TAB(71)'KN/M'
900 PRINT #1
910 FOR Z=1 TO 100
920 IF VF2(5*Z)=0 THEN 940
930 PRINT
#1,TAB(7);VF2(5*Z);TAB(18);VF2(5*Z+1);TAB(36);VF2(5*Z+2);TAB(50);VF2(5*Z+3);TAB(67);VF2(5
940 NEXT Z
950 CLOSE #1% / CLOSE #2%
960 PRINT #1, 'END OF ACCESS.BAS.... PROGRAM BY D.S.SALUNDERS'
970 END

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(b) Program listings for VAX 11/780 Computer

(1) V.BAS

```
100 REM ...AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGANIZATION
110 REM ...MATERIALS RESEARCH LABORATORIES
120 REM PROGRAM TO READ BINARY FILE OF THE RT11 FORMAT
130 INPUT "INPUT FILENAME ($$$$ .DAT;#) IS A PDP11 VIRTUAL FILE := ",FILENAME$
140 INPUT "OUTPUT FILE NAME ($$$$ .OUT;#) := ",FILENAME2$
150 MAP (A) REAL VT2(127)
160 OPEN FILENAME$ FOR INPUT AS FILE #1%, &
      VIRTUAL, &
      RECORDSIZE 512%, &
      MAP A
170 OPEN FILENAME2$ FOR OUTPUT AS FILE #2%, RECORDSIZE 132%
180 K%=0%
190 FOR J%=1% TO 79%
200 FIND #1%, RECORD J%
210 GET #1%
220 FOR I=0 TO 127
230 K%=K%+1%
240 IF K%>5% THEN
      PRINT #2%,VT2(I),
    ELSE
      K%=0%
      PRINT #2%,VT2(I)
    END IF
250 NEXT I
260 NEXT J%
270 PRINT "END OF V.BAS.....PROGRAM BY D.WALKER 1984".
280 END
```

(2) JRERUN.BAS

```

100 REM ...AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGANIZATION
110 REM ...MATERIALS RESEARCH LABORATORIES
120 REM JRERUN...THIS PROGRAM WILL RE-RUN A J TEST USING THE DATA FILES FROM THE PDP11
130 PRINT TAB(5);"*****"
140 PRINT TAB(5);"JRERUN, A PROGRAM TO RE-RUN THE J TEST USING THE DATA FILES"
150 PRINT TAB(5);"FROM THE PDP11.....EDIT LINES 1860-1960 TO CHANGE"
160 PRINT TAB(5);"THE COMPLIANCE CALIBRATION FOR THE MEASUREMENT OF CRACK"
170 PRINT TAB(5);"LENGTH FROM THE UNLOADS (Z9-3 IN THE TEST DATA FILE)"
180 PRINT TAB(5);"*****"
190 INPUT "<CR> TO CONTINUE";X3
200 PRINT TAB(5);"*****"
210 PRINT TAB(5);"THE PROGRAM TAKES THE DATA FILE CREATED FROM THE PDP11/04"
220 PRINT TAB(5);"DISC, AS FILE name.OUT;#, AND READS EACH LINE TO DETERMINE"
230 PRINT TAB(5);"THE Z9 VALUE. WHEN Z9-3 DATA IS EXTRACTED FROM THE FILE AND"
240 PRINT TAB(5);"UNLOADING COMPLIANCE CALIBRATION IS USED TO MEASURE DELTA A"
250 PRINT TAB(5);"THE J VALUES ARE CALCULATED FROM THE DATA STORED IN THE FILE"
260 PRINT TAB(5);"*****"
270 INPUT "<CR> TO CONTINUE";X3
280 PRINT TAB(5);"*****"
290 PRINT TAB(5);"SPECIMENS FOR WHICH UNLOADING COMPLIANCE CALS. ARE AVAILABLE"
300 PRINT TAB(5);"SPECIMEN GEOMETRY AND CALIBRATION";TAB(55);"TYPE"
310 PRINT TAB(5);" MRL J03 / PAFEC 1984";TAB(57);"1" / PRINT
320 PRINT TAB(5);" MRL J03 / EXPERIMENT";TAB(57);"2" / PRINT
380 PRINT TAB(5);"*****"
390 INPUT "INPUT THE SPECIMEN TYPE ";TYPE% / PRINT
400 IF TYPE%<2 GOTO 430
410 PRINT "INVALID SPECIMEN TYPE " / PRINT
420 GOTO 280
430 ON TYPE% GOSUB 1860,1910
440 PRINT "POLYNOMIAL COEFFS FOR TYPE ";TYPE%;" SPECIMEN"
450 PRINT NOTES
460 PRINT "X0- ";X0 / PRINT "X1- ";X1 / PRINT "X2- ";X2
470 PRINT "X3- ";X3 / PRINT "X4- ";X4 / PRINT
480 INPUT "IS THIS CALIBRATION THE ONE REQUIRED? Y/N ";A3
490 IF A3="N" GOTO 280
500 PRINT / PRINT
510 PRINT "***** STARTING TO RERUN THE DATA *****"
520 PRINT / PRINT
530 MAP (A) STRING NN - 132%
540 INPUT "WHAT IS THE OUTPUT DATA FILE NAME, VIZ name ";T3
550 OPEN T3+"OUT" FOR INPUT AS FILE #1%,SEQUENTIAL,RECORDTYPE ANY &, RECORDSIZE 132%, MAP A
560 INPUT "HOW MANY READINGS IN THE FILE";Q%
570 INPUT "WHAT IS THE MERKLE-CORTEN COEFF FOR THIS SPECIMEN ";MCC
580 DIM P(50%),L(50%),A(50%),N(50%)
590 DIM R5(50%),DA5(50%),A5(50%),U5(50%),J5(50%)
600 DIM F5(50%),V5(50%),C5(50%)
610 Z9%-2% / N7%-0%
620 GET #1%
630 SN3=SEGS(NN,43,51)
640 PRINT SN3;" BITS/KN"
650 RN3=SEGS(NN,57,61)
660 PRINT RN3;" BITS/MM"

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```

670 TNS-SEGS(NN,1,13)
680 TNS-TRMS(TNS)
690 PRINT "SPECIMEN THICKNESS AND WIDTH SHOULD BE MEASURED WITH A MICROMETER."
700 INPUT "SPECIMEN THICKNESS (METRES)";B
710 UNS-SEGS(NN,14,19)
720 INPUT "SPECIMEN WIDTH (METRES)";W
730 VNS-SEGS(NN,28,37)
740 PRINT "YOUNG'S MODULUS=";VNS;"Pa"
750 M=VAL(VNS)
760 INPUT "DO YOU WISH TO CHANGE YOUNG'S MODULUS, Y/N ";SS
770 IF SS="N" GO TO 800
780 INPUT "WHAT IS THE NEW YOUNG'S MODULUS, ... IN GPa ";M
790 M=M*1E+09
800 PRINT B,W,M
810 N3=VAL(SNS)
820 N4=VAL(RNS)
830 K=N3/(N4*1.0E+06)
840 FOR I%=1% TO Q%
850 GET #1%
860 SNS-SEGS(NN,58,58)
870 Z%=VAL(SNS)
880 IF Z%=1% GO TO 920
890 IF Z%=2% THEN N%=0%
900 IF Z%=(Z9%-1%) THEN GOSUB 1200
910 IF Z%=3% THEN GOSUB 950
920 NEXT I%
930 IF Z%=3% THEN GOTO 1200
940 GO TO 1620
950 REM DATA ACQUISITION FROM PDP11 DATA FILE VF1
960 IF N%>0% THEN GOTO 1000
970 PRINT PRINT PRINT
980 PRINT "UNLOADING COMPLIANCE DATA" PRINT
990 PRINT "READING","LOAD","DISPL.", "AREA"
1000 N1S-SEGS(NN,1,5)
1010 N2S-TRMS(N1S)
1020 N6%=VAL(N2S)
1030 P1S-SEGS(NN,10,23)
1040 P2S-TRMS(P1S)
1050 P=VAL(P2S)
1060 L1S-SEGS(NN,23,35)
1070 L2S-TRMS(L1S)
1080 L=VAL(L2S)
1090 A1S-SEGS(NN,38,53)
1100 A2S-TRMS(A1S)
1110 A=VAL(A2S)
1120 P(N%)-P
1130 L(N%)-L
1140 A(N%)-A
1150 N(N%)-N6%
1160 PRINT N(N%),P/N3,L/N4,A/(N3*N4)
1170 N%-N%*1%
1180 Z9%-Z% / N5%-N%
1190 RETURN
1200 PRINT / PRINT / PRINT
1210 PRINT "UNLOADING COMPLIANCE RERUN"
1220 REM SETTING SUMMATIONS TO ZERO

```

```

1230 E1=0 / E2=0 / E3=0 / E4=0 / E5=0 / E6=0
1240 E7=0 / E8=0 / E9=0 / E10=0 / F=0
1250 PRINT "MAX. NO. OF UNLOADING POINTS IS ";N5%
1260 INPUT "HOW MANY OFF THE MAX. LOAD ARE TO BE DISCARDED ";O%
1270 IF O%>(N5%-10%) THEN PRINT "ERROR IN INPUT, TRY AGAIN" / GOTO 1250
1280 IF O%=0 THEN PRINT "DISCARD OF ZERO POINTS IS OK? <Y/N> " / INPUT Z5 / IF Z5<>"Y" GOTO
1290 FOR C%=(0%+O%) TO (N5%-1%) STEP +1%
1300 E1=E1+P(C%) / E2=E2+L(C%) / E3=E3+P(C%)*L(C%)
1310 E4=E4+L(C%) 2% / E6=E6+P(C%) 2%
1320 F=F%+1%
1330 NEXT C%
1340 REM CALCULATION OF SLOPE
1350 E8=E3-((E1*E2)/F%) / E9=E4-((E2 2%)/F%)
1360 E5=E8/E9
1370 REM CALCULATION OF CORRELATION COEF.
1380 E10=E6-((E1 2%)/F%)
1390 E7=(E8 2)/(E9*E10)
1400 V=(K*M*B)/E5 / REM NORMALIZED COMPLIANCE
1410 V5(N7%)=V / C5(N7%)-E7
1420 R=X0+X1*V+X2*V 2%+X3*V 3%+X4*V 4%
1430 IF N7%>=1% GOTO 1450
1440 Y1=R*W / Y0=Y1 / GOTO 1460
1450 Y1=R*W
1460 PRINT "CHECK OF NO OF UNLOADING POINTS ";F%;" SHOULD BE ";N5%-O%
1470 PRINT "CRACK LENGTH- ";Y1;" METRES"
1480 PRINT "READING", "DATA POINTS", "NORM. COMPL.", "CORR. COEF.", "AREA", "A/W", "DELTA A", "J"
1490 J=MCC*A(C%)/(B*(W-Y1)*N3*N4*1000)
1500 U=N6%-N5%+1%
1510 PRINT U,F%,V,E7,A(C%)/(N3*N4%),R,Y1-Y0,J
1520 Z9%-Z%
1530 U5(N7%)=U / A5(N7%)-A(C%)/(N3*N4%) / R5(N7%)-R
1540 DA5(N7%)=Y1-Y0 / J5(N7%)-J / F5(N7%)-F%
1550 INPUT "<CR> TO PROCEED TO NEXT UNLOADING SET ";X5
1560 N7%=N7%+1%
1570 IF 1%<O% THEN GOTO 1610
1580 PRINT "LAST UNLOADING DATA SET"
1590 INPUT "SET PRINTER AND <CR> FOR PRINT OUT OF UNLOADING COMPLIANCE CALCS";X5
1600 GOTO 1620
1610 RETURN
1620 CLOSE #1%
1630 PRINT / PRINT / PRINT
1640 PRINT "SUMMARY OF UNLOADING COMPLIANCE CALCULATIONS"
1650 PRINT "RUN USING JRERUN.BAS ON THE VAX11/780"
1660 PRINT "USING PDP11/04 DATA FILE ";T5;"(RUN THROUGH V.BAS)"
1670 PRINT
1680 PRINT "YOUNG'S MODULUS FOR THESE CALCULATIONS -";M;"Pa"
1690 PRINT "SPECIMEN THICKNESS-";B;"metres"
1700 PRINT "SPECIMEN WIDTH -";W;"metres" / PRINT
1710 PRINT NOTES
1720 PRINT "POLYNOMIAL FIT COEFFS"
1730 PRINT "X0- ";X0;" X1- ";X1;" X2- ";X2
1740 PRINT "X3- ";X3;" X4- ";X4
1750 PRINT
1760 PRINT "MERKLE-CORTEN COEFF- ";MCC
1770 PRINT / PRINT
1780 PRINT "READING", "DATA POINTS", "NORM COMPL", "CORR COEF.", "AREA", "A/W", "DELTA A", "J VALUE

```

```

1790 FOR N%=0% TO N7%-1%
1800 PRINT U5(N%),F5(N%),V5(N%),C5(N%),A5(N%),R5(N%),DA5(N%),J5(N%)
1810 NEXT N%
1820 PRINT / PRINT
1830 PRINT "THIS FILE WILL BE STORED AS ";T5;" .DAT"
1840 PRINT "RUN JPRINT TO RETRIEVE THIS FILE"
1850 GOTO 2110
1860 REM COMPLIANCE CALIBRATIONS (POLYNOMIAL FITS)
1870 NOTES="J03 CAL. FROM PAFEC 1984"
1880 X0=7.4857727E-02 / X1=1.7894292E-02 / X2=-2.3063905E-04
1890 X3=1.5006292E-06 / X4=-3.7869343E-09
1900 RETURN
1910 REM
1920 NOTES="J03 CAL. FROM CLARK EXPT. DATA"
1930 X0=1.0697574E-01 / X1=1.4754694E-02 / X2=-1.6242350E-04
1940 X3=8.7544527E-07 / X4=-1.7795666E-09
1950 RETURN
1960 REM
2110 REM PROGRAM TO WRITE A SUMMARY OF THE JRRUN CALCULATIONS AS A FILE name.DAT
2120 OPEN T5+" .DAT" FOR OUTPUT AS FILE #2%, ORGANIZATION SEQUENTIAL, RECORDTYPE ANY
2130 PRINT #2%, T5
2140 PRINT #2%,M
2150 PRINT #2%,B
2160 PRINT #2%,W
2170 PRINT #2%,NOTES
2180 PRINT #2%,X0 / PRINT #2%,X1 / PRINT #2%,X2 / PRINT #2%,X3 / PRINT #2%,X4
2190 PRINT #2%,MCC
2200 R%=N7%-1%
2210 PRINT #2%,R%
2220 FOR N%=0% TO R%
2230 PRINT #2%,U5(N%)
2240 PRINT #2%,F5(N%)
2250 PRINT #2%,V5(N%)
2260 PRINT #2%,C5(N%)
2270 PRINT #2%,A5(N%)
2280 PRINT #2%,R5(N%)
2290 PRINT #2%,DA5(N%)
2300 PRINT #2%,J5(N%)
2310 NEXT N%
2320 CLOSE #2%
2330 PRINT / PRINT
2340 PRINT "END OF JRRUN.BAS.....program by D.S.Saunders and I.A.Burch 1985"
2350 END

```

(3) ACCESS1.BAS

```
REM ...AUSTRALIAN GOVERNMENT DEFENCE SCIENTIFIC AND TECHNOLOGY ORGINIZATION
110 REM ...MATERIALS RESEARCH LABORATORIES
120 REM THIS PROGRAM WILL ACCESS OUTPUT FILES FOR TEST DATA FOR THE VAX 11/780
130 PRINT TAB(5);"*****"
140 PRINT TAB(5);"ACCESS1, A PROGRAM TO CONVERT A J INTEGRAL TEST DATA FILE"
150 PRINT TAB(5);"INTO A PLOTTING DATA FILE FOR USE WITH THE KENNETT PLOT ROUTINE"
160 PRINT TAB(5);"*****"
170 PRINT TAB(5);"THE PROGRAM TAKES THE DATA FILE CREATED FROM THE PDP11/04"
180 PRINT TAB(5);"DISK, AS FILE $$$$OUT;#, AND WRITES A NEW FILE (FORCE/DISPL.)"
190 PRINT TAB(5);"NAME THIS FILE $$$$GRA;#"
200 PRINT TAB(5);"THE PROGRAM WILL RECORD THE VAX DATA FILE FROM WHICH $$$$GRA;# IS CREATED"
210 PRINT TAB(5);"*****"
220 MAP (A) STRING NN = 132%
230 INPUT "WHAT IS THE OUTPUT FILE NAME, VIZ $$$$OUT;#. ";T$
240 OPEN T$ FOR INPUT AS FILE #1%,SEQUENTIAL,RECORDTYPE ANY &,RECORDSIZE 132%, MAP A
250 INPUT "WHAT IS THE PLOTTING FILE NAME, VIZ $$$$GRA;#. ";S$
260 OPEN S$ FOR OUTPUT AS FILE #2%,ORGANIZATION SEQUENTIAL VARIABLE
270 INPUT "WHAT IS THE FIRST READING NUMBER YOU WANT TO ACCESS";P%
280 INPUT "WHAT IS THE LAST READING NUMBER YOU WANT TO ACCESS";Q%
290 GET #1%
300 SN$-SEGS(NN,43,51)
310 PRINT SN$
320 RN$-SEGS(NN,57,61)
330 PRINT RN$
340 N3=VAL(SN$)
350 N4=VAL(RN$)
360 PRINT TAB(20);"SELECTED FORCE/DISPLACEMENT DATA FROM";T$
370 PRINT TAB(20);"WRITTEN INTO PLOTTING FILE ";S$
380 PRINT TAB(20);"SCALING CONSTANTS FOR THE TEST"
390 PRINT TAB(20);"FOR LOAD, RO= ";N3;TAB(50);"BITS/KN"
400 PRINT TAB(20);"FOR DISPL, R1= ";N4;TAB(50);"BITS/MM"
410 PRINT / PRINT
420 PRINT #2%,"DISPLACEMENT IN MM"
430 PRINT #2%,1%;"."
440 PRINT #2%,"FORCE IN KN"
450 PRINT #2%,1%;"."
460 U$-LEFT$(T$,4)
470 PRINT #2%,"DATA FROM ORIGINAL ON PDP11/04 DISK. AS ";U$;".DAT"
480 PRINT TAB(5);"READINGS NO ";P%;" TO ";Q%; "INCLUSIVE"
490 PRINT / PRINT
500 B%--((Q%-P%)+1)
510 PRINT #2%,B%
520 PRINT #2%,"PLOTTING DATA FROM ";T$;"READING NOS ";P%;"TO ";Q%;"INCL"
530 FOR I% = 1% TO 2000%
540 GET #1%
550 NNW$-RIGHT$(NN,7)
560 N1$-LEFT$(NNW$,17)
570 N2$-SEGS(NNW$,18,33)
580 N1=VAL(N1$)
590 N2=VAL(N2$)
600 IF I%<P% THEN 640
610 IF I%>Q% THEN 650
```

```
620 PRINT N2/N4%,N1/N3
630 PRINT #2%,N2/N4%;", ";N1/N3
640 NEXT I%
650 CLOSE #1% / CLOSE #2%
660 PRINT "END OF ACCESS.BAS.....Program by D.S.Saunders"
670 END
```

APPENDIX 2

Listings of Elastic Unloading Compliance for a Range of Specimen Geometries

(A) MRL J03 (Compact Tension Specimen)

(1) PAFEC - generated (1984) [1]

$EB \frac{V_{LL}}{P}$	a/W
18.0958	0.3
19.0547	0.32
20.3038	0.34
21.7481	0.36
23.563	0.38
25.4099	0.4
27.4611	0.42
29.7407	0.44
32.4349	0.46
35.3034	0.48
38.5184	0.5
42.1361	0.52
46.2305	0.54
50.2362	0.58
62.4079	0.6
69.5932	0.62
78.0284	0.64
88.0301	0.66
100.013	0.68
113.907	0.7
131.604	0.72
153.631	0.74
181.487	0.76
217.361	0.78
264.575	0.8

(2) PAFEC-generated (1985) [2], Point Pin Loading

$EB \frac{V_{LL}}{P}$	a/W
22.76	0.36
26.62	0.40
31.39	0.44
37.34	0.48

44.74	0.52
54.43	0.56
67.30	0.60
85.00	0.64
109.9	0.68
147.5	0.72
207.3	0.76

The second PAFEC-generated compliance calibration [2] is now considered to be more accurate than (1), above. For this calibration the original mesh was modified slightly and the normalised compliance data is close to the experimental data given in [3] and reproduced below.

EB $\frac{V_{LL}}{P}$	a/W
24.78	0.378
26.64	0.393
29.58	0.419
40.76	0.493
41.6	0.495
41.65	0.497
40.58	0.498
41.63	0.498
42.76	0.507
44.5	0.517
53.47	0.544
55.15	0.561
57.75	0.565
59.43	0.567
90.6	0.644
110.3	0.670
154.0	0.722
167.0	0.735
209.0	0.763
212.1	0.764
215.9	0.767
225.7	0.768
224.9	0.773
242.5	0.778
251.9	0.784
278.0	0.793

(B) ASTM E 399 (Compact Tension Specimen), [4],[5]

EB $\frac{V_{LL}}{P}$	a/W
8.6	0.2
11.18	0.25
14.28	0.30
18.09	0.35

22.86	0.40
28.96	0.45
36.99	0.50
47.90	0.55
63.35	0.60
86.36	0.65
122.80	0.70
185.40	0.75
304.6	0.80
578.36	0.85
1389.07	0.90
5952.20	0.95

References

- (1) Heller, M. (1984). Private communication, Australian DSTO Aeronautical Research Laboratories.
- (2) Heller, M. and Paul, J. (1985). "Numerical Compliance and Stress Intensity Factor Calibrations for MRL Compact Specimens", Aeronautical Research Laboratories Structures Technical Memorandum, 421.
- (3) Clark, G. (1983). "Elastic-Plastic Fracture Toughness Testing of Medium Strength Gun Steels", Proc. Workshop, Welding Institute, Abington, U.K., June 1983, Sponsored by the Technical Co-operation Program, Sub Group P, Technical Panel P-1, paper No. 2 - limited release -.
- (4) Saxena, A. and Hudak, S.J., (1978). "Review and Extension of Compliance Information of Common Crack Growth Specimens". Int. J. of Fracture, 14, pp 453-468.
- (5) Newman, J.C., (1976). "Crack Opening Displacements in Center Crack, Compact and Crack Line Wedge Loaded Specimens". NASA Technical Note, D-8268.

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A1	Area	This is the area under the linear-elastic part of the load/load-line-displacement record and is calculated as the area of the P/D triangle to P7.
A3	Area	This area is continuously updated for each displacement increment, viz Z9=1, Z9=2, but not when Z9=3 or Z9=4. A3 at the final load increment before the unload is written into the virtual files VF1, VF2. A3 is not increased again until Z9 returns to a value of 2.
E5	Raw compliance	This value from the linear regression of the unloading data.
V	Normalized compliance	$E5 \times E \times B \times P \times \frac{RI}{RO}$
R	a/W	This value is calculated from the unloading compliance calibration polynomial (f(v)).
Y1	Crack length	$R * W$
D5	Displacement (bits)	Average of 10 values
P5	Load (bits)	Average of 10 values
D9	Displacement (bits)	Displacement at the commencement of unloading.

(1) See listing 3

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APPENDIX 5

Example of an Output from JRRUN.BAS

SUMMARY OF UNLOADING COMPLIANCE CALC'S
JRRUN PDP11/04 DATA FILER AND RUN ON THE PDP11/04
FOR FILE R1

YOUNG'S MODULUS FOR THESE CALCULATIONS = 2.03000E+11 PA
SPECIMEN THICKNESS = .0254 METERS
SPECIMEN WIDTH = .050868 METERS

103 CAL. FROM CLARK EXPT DATA. 1983
POLYNOMIAL FIT COEFFS
X0= .106876 X1= .0147547 X2=-1.87423E-04
X3= 8.75445E-07 X4=-1.77857E-08 X5= 0

HERKLE-CORTEN COEFF= 2.218

READING # AT TOP OF INCL	TOTAL NO. OF DATA POINTS	DATA POINTS USED	NORM COMPL.	CORR COEFF	AREA	A/W	DELTA A	J VALUE
247	26	22	63.4018	.888748	8.51245	.583808	0	35.0181
351	27	23	62.7387	.888602	8.32423	.581888	-8.87742E-03	38.1788
415	28	24	63.4748	.888888	10.1235	.584118	1.07884E-05	41.8888
482	27	23	64.0848	.889576	10.8828	.585871	1.00141E-04	45.385
545	27	23	62.8442	.888772	11.8088	.58257	-8.80778E-05	48.8335
611	28	25	63.8825	.888748	12.8068	.58466	3.84818E-05	53.1822
680	28	25	63.7058	.888417	13.8388	.584785	4.48041E-05	57.4545
749	27	23	63.8838	.888781	14.8488	.585238	8.78512E-05	61.8843
820	31	27	64.2802	.888428	15.8485	.586388	1.25552E-04	68.0032
892	31	27	64.312	.888825	17.0888	.588518	1.33047E-04	70.8838
885	32	28	64.4281	.888511	18.241	.588338	1.48488E-04	75.5718
1038	32	28	65.1152	.888438	18.5528	.588787	2.47788E-04	81.3866
1111	32	28	65.372	.88888	20.7037	.588478	2.83828E-04	88.3258
1184	33	28	65.3748	1.00002	21.8119	.588484	2.84335E-04	91.3853
1280	34	30	65.7284	1.00025	23.0584	.590458	3.33882E-04	98.3854
1338	34	30	68.2488	.888874	24.2077	.581858	4.03318E-04	101.525
1412	35	31	68.3814	1.00003	25.3858	.582188	4.21004E-04	108.548
1487	31	27	67.7004	.888757	26.8873	.585687	6.00880E-04	113.878
1555	36	32	68.2048	.888578	28.2223	.58852	7.85880E-04	120.828
1634	34	30	68.4324	.888852	28.4878	.600088	8.24875E-04	128.257
1708	35	31	70.227	.888858	30.8007	.802038	9.24053E-04	132.479
1788	33	28	70.5181	1.00018	32.041	.60274	8.58863E-04	138.058
1857	33	28	70.8113	1.00008	33.3275	.603683	1.00804E-03	143.843
1928	31	27	72.3234	1.00027	34.817	.608888	1.17888E-03	152.078

END OF JRRUN.BAS... PROGRAM BY D.S.SAUNDERS AND I.A.BURCH.....1988

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